AgroBioHeat

PROMOTING THE PENETRATION OF AGROBIOMASS HEATING
IN EUROPEAN RURAL AREAS

MAIZE RESIDUES TO ENERGY

UABIO

CERTH
CENTRE FOR
RESEARCH & TECHNOLOGY
HELLAS

This project has received funding from the
European Union's Horizon 2020 research and innovation
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ABOUT THIS PUBLICATION

The publication «Maize residues to Energy», made by the Bioenergy Association of Ukraine (UABIO) and Centre for Research and Technology Hellas (CERTH), is part of a series of authoritative guides prepared within the framework of the AgroBioHeat project that aim to provide a systematic knowledge about the utilization of different types of agrobiomass resources. In particular, it focuses on the residues of maize (also known as corn) cultivation and how this biomass resource – produced annually in vast quantities and currently underutilized – can be effectively harvested and used for the production of bioenergy.

The AgroBioHeat project aims to produce a mass deployment of improved and market ready agrobiomass heating solutions in Europe. Agrobiomass is a large, underexploited and indigenous resource, which can support the achievement of the European Energy and Climate targets, while promoting rural development and circular economy. The project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 818369.

For more information about the project, please visit www.agrobioheat.eu

AUTHORS
Georgii Geletukha, Semen Drahniev, Tetiana Zheliezna/
Bioenergy Association of Ukraine (UABIO)
Manolis Karampinis/
Centre for Research & Technology Hellas (CERTH)

DESIGN & LAYOUT
Olga Nikitina
olik5981@gmail.com

ABBREVIATIONS

Abbreviation	Explanation
CB	Cobs
CCM	Corn-cob-mix
CHP	Combined heat and power
d.b.	Dry base
DM	Dry matter
E	Ears
ESP	Electrostatic Precipitator
EW	Ear wrap
GHG	Greenhouse gas
GR	Grain
LV	Leaves
Mgy	Million gallons per year
MY	Marketing year
OGC	Organic Gaseous Compounds
PTO	Power take-off
ST	Stalks
TSP	Total particulate matter
VS	Volatile solids
W	Water content
w.b.	Wet basis

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INTRODUCTION

Maize (also called corn in the United States) is one of the most important crops in the world. It is a highly productive plant of tropical origin and C4 carbon fixation. Its origin is from the Andean region of Central America, which explains the need for heat for its growth and development. In a short time, maize produces more organic matter than other crops. This cereal is grown for grain and forage (silage or directly consumed by animals without silage). Corn is often used with the meaning of maize grain[1], the world production of which was from 972 to 1123 Mt per year in 2015-2019. In the 2019/2020 marketing year (MY), the EU produced 65 Mt of corn or almost 6% of the world production[2]. In Ukraine, the production of corn has exceeded wheat production, and maize has become a main crop in the country by the gross harvest. The valuable properties of corn cause its constantly high demand in the world and the European market. The average corn yield has been higher than 7 t/ha in the EU and Ukraine recent years.

In addition to grain, a considerable amount of maize residues[3] (stalks, leaves, cobs, husks, etc.) are formed. They can be harvested and used for different purposes as agrobiomass, including bioenergy. Collected and taken from fields, maize residues are considered as maize by-products. For example, they can be used as feedstock for the production of solid biofuels, biogas, and second-generation liquid biofuels. But now maize residues are a large, underused, and local renewable resource, which could support the achievement of the European Energy and Climate targets while promoting rural development and circular economy.

Maize residues have specific fuel properties, which requires the use of specially designed boilers for burning this type of agrobiomass. Economically feasible use of this biomass also depends on the appropriate value chain “harvesting – logistics – storage”. These issues and biomass potential of maize residues for energy in the EU and Ukraine, the possibility of processing this agrobiomass into pellets/briquettes, biogas, and second-generation liquid biofuel, sustainability aspects are described in this guide.

[1] In this document, corn and maize grain are used as synonyms.
[2] World Agricultural Production, USDA Reports https://apps.fas.usda.gov/psdonline/circulars/production.pdf
[3] The aboveground part of maize grown for grain and left in the field following the harvest (mainly stalks, leaves, husks, and cobs) is often referred to as “corn stover” or “maize straw”.

MAIZE RESIDUES AS A SOURCE OF ENERGY

MAIZE IN CROP PRODUCTION

Maize dominates in crop production globally due to the possibility of its growing in various places with high yields and the increasing demand for corn that is used for the production of a wide range of products, including biofuels. In the world, about 60% of bioethanol is produced from corn[4]. In 2019, almost 30% of corn (105.6 Mt) was used for the production of the first generation of bioethanol in the USA[5].

The USA is the world leader in corn production and yields (Table 1). The EU is the 4th largest corn producer in the world, and Ukraine ranks 6th. According to the preliminary data, the production of corn in the USA in 2020/2021 MY was 358.5 Mt (32% of the global production), the average yield was 10.8 t/ha. In other countries, the production of corn in 2020/2021 MY was the following: China – about 260.7 Mt, Brazil – 87 Mt, the EU – 67.1 Mt, Argentina – 50.5 Mt, India – 31.5 Mt, and Ukraine – 30.3 Mt. The USDA forecasts[6] for 2021/2022 MY are 70.4 Mt for the EU and 40.0 Mt for Ukraine, which is more than the previous year. It should be noted that in the EU, green maize, grown mainly for silage, also occupies a large area. Thus, in 2019, the area of harvested green maize was 6.4 million hectares, whereas the area of grain maize and corn-cob-mix was 8.9 million hectares[7]. The total area under maize was almost 14.5% of arable lands in the EU28, and above 18.5% in Ukraine.

TABLE 1:
Main producers of corn in the world over the last 5 years (by MY)[6]

No.	Country/ region	Area, Mha					Yield, t/ha					Production, Mt				
		2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	2017/ 2018	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022
1	USA	33.5	32.9	32.9	33.3	34.4	11.1	11.1	10.5	10.8	11.1	371.1	364.3	346.0	358.5	382.6
2	China	42.4	42.1	41.3	41.3	43.3	6.1	6.1	6.3	6.3	6.5	259.1	257.2	260.8	260.7	272.6
3	Brazil	16.6	17.5	18.5	19.9	20.8	4.9	5.8	5.5	4.4	5.7	82.0	101.0	102.0	87.0	118.0
4	EU	8.3	8.3	8.9	9.3	9.4	7.5	7.8	7.5	7.2	7.5	62.0	64.4	66.7	67.1	70.4
5	Argentina	5.2	6.1	6.3	6.4	6.8	6.2	8.4	8.1	7.9	8.0	32.0	51.0	51.0	50.5	54.5
6	Ukraine	4.4	4.6	5.0	5.4	5.4	5.4	7.8	7.2	5.6	7.4	24.1	35.8	35.9	30.3	40.0
7	India	9.4	9.0	9.6	9.9	9.7	3.1	3.1	3.0	3.2	3.1	28.8	27.7	28.8	31.5	30.0
8	Mexico	7.3	7.2	6.6	7.1	7.3	3.8	3.8	4.0	3.8	3.8	27.6	27.6	26.7	27.4	28.0
	World	**192.2**	**192.1**	**193.6**	**198.8**	**203.0**	**5.6**	**5.9**	**5.8**	**5.7**	**6.0**	**1080**	**1123**	**1120**	**1123**	**1209**

NOTES: 2020/2021 MY – preliminary data, 2021/2022 MY – projection (December 2021).

[4] *OECD FAO Agricultural Outlook 2019 2028. http://www.fao.org/3/ca4076en/ca4076en.pdf*
[5] *World of corn 2020. http://www.worldofcorn.com/pdf/WOC-2020.pdf*
[6] *World Agricultural Production, USDA Reports https://apps.fas.usda.gov/psdonline/circulars/production.pdf*
[7] *Eurostat https://ec.europa.eu/eurostat/web/main/home*

The increase in corn yields during the last decades (Fig. 1) is associated with the development of agricultural science and the use of biotechnology for the formation of hybrids. In comparative tests, the American farmers managed to achieve yields of corn at the level of over 25.0 t/ha. In 2019, the USA National Corn Growers Association announced the world record in Virginia near 38.7 t/ha (616.2 bushels/acre) of grain corn[8]. The growth of average global maize yield (2016-2018) by 14% is expected until 2028[4].

The distribution of actual yield and harvested production of grain maize and corn-cob-mix in EU28 countries is shown in Fig. 2. Among these, grain maize prevails. The lead corn producers were Romania (17.3 Mt in 2019), France (13.0 Mt in 2019), and Hungary (8.3 Mt in 2019). From 2015 to 2019, the highest average yield of grain maize and corn-cob-mix was achieved in Spain (11.6 t/ha), Greece (10.3 t/ha), Austria, and Italy (10.1 t/ha).

MAIZE RESIDUES

The main product of grain maize cultivation is grain, which is the economic reason for the farmers' activity. In addition, the maize plant consists of different underground and aboveground parts (Fig. 3), which form maize residues. It is important to note that for maize the ration residue/grain is significantly higher than for other cereals. According to experimental data, biomass formation in leaves and stems of maize can be high even in conditions of moderate water stress, which makes this crop an important source of agricultural residue biomass[10]. Maize residue yield (R) to grain yield (Y) ratio (R/Y) depends on many factors, primarily on plant variety, farming practices, climate, and field conditions[11]. In general, this ratio (R/Y) is reduced with the increase of corn yield (Fig. 4), but the relationship between residue yield and corn yield is weak. It is convenient to use the standard ratio R/Y. For example, in Ukraine, the typical R/Y = 1.3. During harvesting, the moisture content of corn grain and maize residues can be different, and the described approach does not take this into account. Often a harvest index (HI) is used for the assessment of residue yield: the ratio of grain to total biomass always refers to dry-matter weight. In the USA, the HI generally fluctuates around 0.50[12], which matches R/Y = 1.

Different correlations for the estimation of the R/Y ratio based on the grain yield are proposed in the scientific literature. In this guide, the equation given by Bentsen et al. [13]is used for the assessment of maize residue biomass potential, since it is considered to provide a good match with the experimental observations:

$$R/Y = 2.656 * \exp(-0.103 * Y),$$

where both R/Y and Y are t/ha dry matter.

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[8] https://www.ocj.com/2019/12/2019-national-corn-yield-contest-hits-new-yield-record/
[9] https://www.nass.usda.gov/Publications/Todays_Reports/reports/croptr18.pdf
[10] Camia A., Robert N., Jonsson R., Pilli R., García-Condado S., López-Lozano R., van der Velde M., Ronzon T., Gurría P., M'Barek R., Tamosiunas S., Fiore G., Araujo R., Hoepffner N., Marelli L., Giuntoli J., Biomass production, supply, uses and flows in the European Union. First results from an integrated assessment, EUR 28993 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN978-92-79-77237-5, doi:10.2760/539520, JRC109869
[11] Maximising the yield of biomass from residues of agricultural crops and biomass from forestry. Final report of Ecofys project. https://ec.europa.eu/energy/sites/ener/files/documents/Ecofys%20-%20Final_%20report_%20EC_max%20yield%20biomass%20residues%2020151214.pdf
[12] https://www.canr.msu.edu/news/harvest_index_a_predictor_of_corn_stover_yield
[13] Bentsen NS, Felby C, Thorsen BJ. Agricultural residue production and potentials for energy and materials services. Progr Energ Combustion Sci 2014;40:59–73. https://doi.org/10.1016/j.pecs.2013.09.003

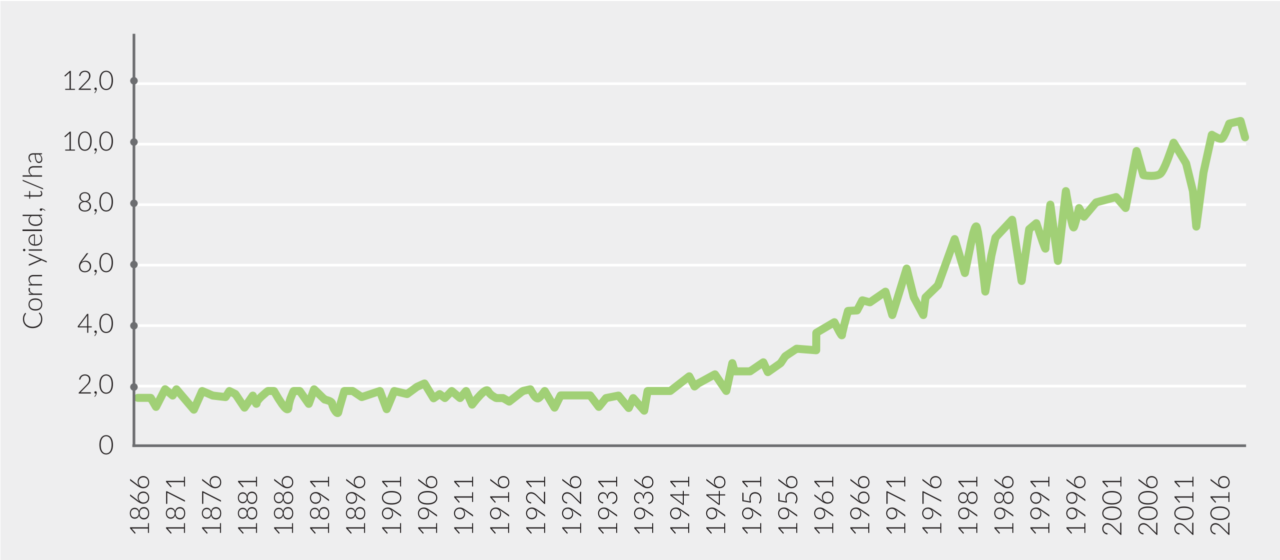

FIGURE 1:
Corn yield in the USA from 1866 to 2019[9]

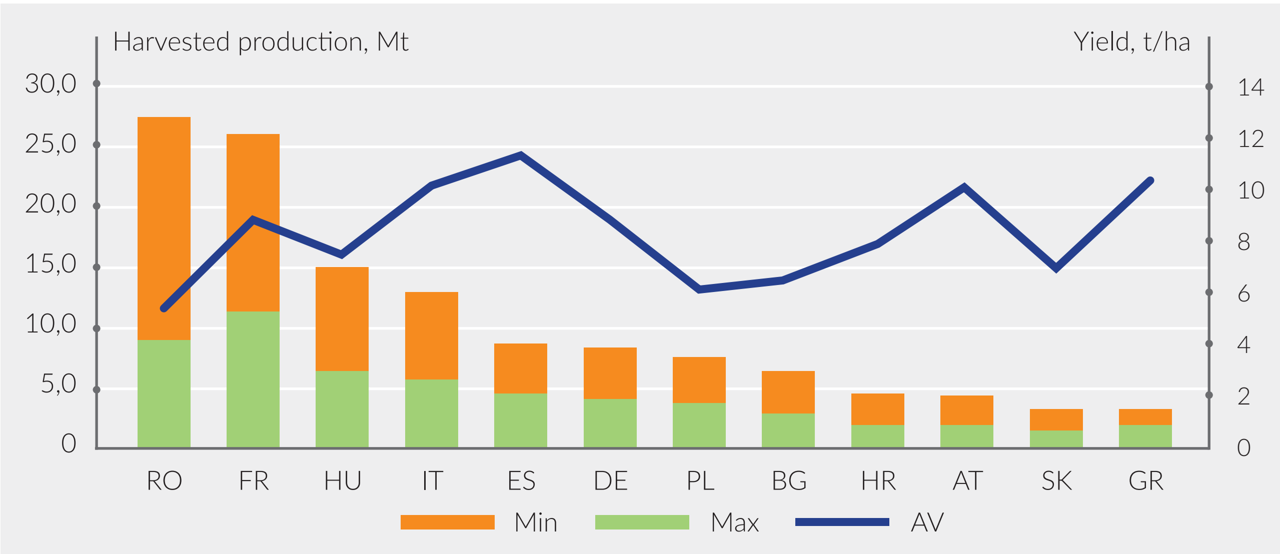

FIGURE 2:
Grain maize and corn-cob-mix production and yield in selected EU countries from 2015 to 2019.
(Source: Eurostat online data code: TAG00093, UABIO elaboration).

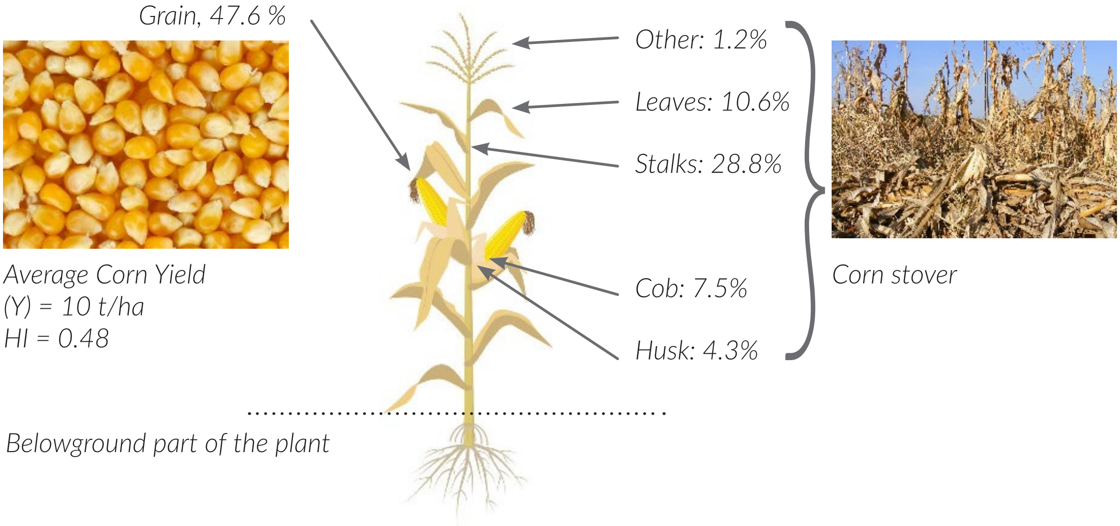

FIGURE 3:
Different aboveground parts of the maize plant and their dry mass ratio[14]

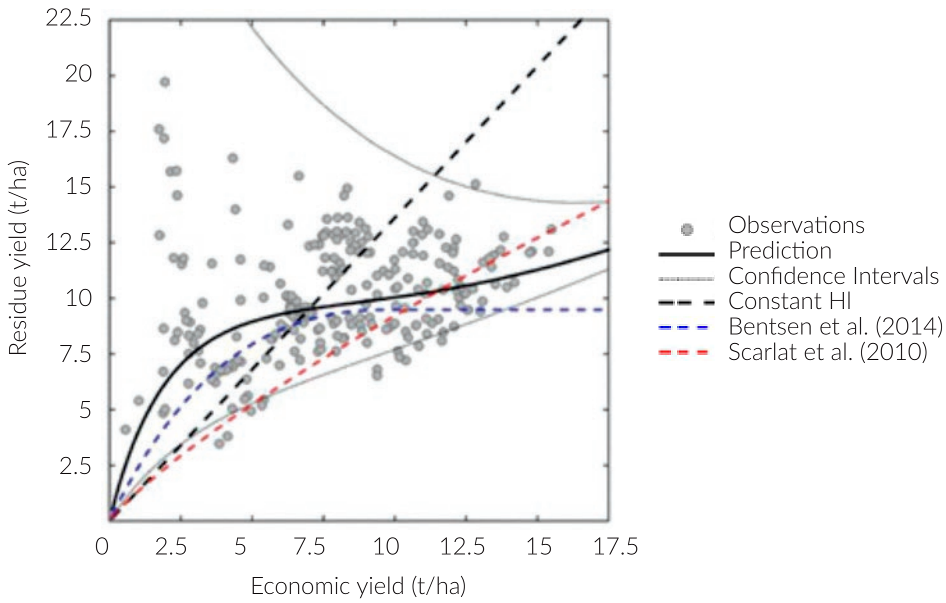

FIGURE 4:
Empirical model computed for the prediction of residue yield for the maize depending on the economic yield of grain[15]

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[14] *David Ertl Sustainable corn stover harvest / Iowa Corn Promotion Board, 2013. – 18 p. https://www.researchgate.net/publication/319493290_Sustainable_Corn_Stover_Harvest_A_publication_of_the_Iowa_Corn_Promotion_Board*

[15] *García-Condado S, López-Lozano R, Panarello L, et al. Assessing lignocellulosic biomass production from crop residues in the European Union: modelling, analysis of the current scenario and drivers of interannual variability. GCB Bioenergy. 2019;00:1–23. https://doi.org/10.1111/gcbb.12604*

FIGURE 5:
Corn stover left in a field after combine harvester

The aboveground residues (corn stover) can be partly collected as maize by-products that have a commercial value (Fig. 5). The rest of the aboveground parts and the underground parts of maize are left in the field as crop residues, which play the role of organic fertilizers. The proper residue management practices are essential for soil quality. Appropriate crop residue removal rates should be based on the minimum level of crop residue that must be kept on land to maintain the soil quality, soil organic matter, and reduce the risk of erosion[16]. The sustainability aspects for maize by-products harvesting are described in Chapter "Sustainability aspects of maize residues utilization" of this guide. The data reported in the literature on the sustainable removal rates of maize residues constitute from 25% to 70%. In this energy biomass potential assessment, the removal rate of 40% for maize residues is considered.

Production of agricultural residues, including maize residues, is seasonable and depends on the harvesting periods. Grain corn is harvested during different time frames, depending on the variety, the place of cultivation, and the time of sowing. Usually, the time frame for corn harvesting is determined by the level of grain moisture, so before harvesting, farmers determine the moisture content of the grain and its ripeness, taking into account the terms of sowing and the hybrid ripeness group. The moisture content of the different maize parts is not homogeneous and rapidly decreases after 120 days from the date of sowing[17]. In Europe, the typical period of maize grain harvesting is September-November. It should be noted that some farmers harvest corn in December, January, and even later. However, it is not due to agro-technical requirements but owing to some production needs and economic

[16] Nicolae Scarlat, Milan Martinov, Jean-François Dallemand Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use / Waste Management, Volume 30, Issue 10, October 2010, Pages 1889-1897. https://doi.org/10.1016/j.wasman.2010.04.016
[17] C. Igathinathane, Alvin R.Womac, Shahab Sokhansanj, Lester O.Pordesimo. Vertical Mass and Moisture Distribution in in Standing Corn Stalks // 2004 ASAE/CSAE Annual International Meeting (Ottawa, Ontario, Canada, 1-4 August, 2004). – 20 p.

feasibility. During the harvest time, corn stover is often wetter (W > 30%) than grain (EU standard humidity is W14%), but after the grain harvest, the moisture of the residues evaporates intensively, for instance, under conditions of wind blowing. Also, the moisture content of maize residues is highly dependent on the weather conditions during harvesting, and intensive rainfalls can lead to very unfavourable conditions for harvesting biomass to be used in energy applications.

The net calorific value (dry base) of 17.5 MJ/kg[18] was used for the calculation of the energy potential of maize residues (Fig. 6). The distribution of the energy potential of maize residues over Europe is not even. In 2019, the largest concentration of maize residues with the energy equivalent of 302.5 PJ was in Ukraine. In the EU, the leaders were Romania (155.2 PJ), France (97.5 PJ), and Hungary (64.8 PJ). The total EU28 energy potential of maize residues was 557.9 PJ in 2019. There is also significant potential in countries such as Spain, Greece, Belgium, Austria, and Turkey.

The realizable energy potential of maize residues is actually determined by farmers. They will provide sustainable corn stover harvesting if they have an economic interest. The cost of maize by-products on the market depends on the agrobiomass characteristics, which are important for the end-users. Different parts of maize by-products have different physicochemical characteristics, but generally, it is lignocellulosic biomass. The main ways of the use of maize grain and residues are shown in Fig. 7. Corn stover has relatively low nutritive value, especially maize stalks, which are considered as low-quality fodder[19]. Maize leaves' and husk's nutritional value is higher compared to maize stalks and cobs, but they are still not used in large volumes. Currently, corn stover is mainly left in the field, plowed, and incorporated in the soil. It should be noted that in some territories, crop residues, including maize residues, are burnt in the fields, which causes numerous negative consequences for the environment[20]. Thus, existing resources of maize by-products could be used as agrobiomass feedstock for solid biofuels, 2nd generation bioethanol, and biogas.

FIGURE 6:
Energy potential of maize residues in Europe (2019)

[18] *Caroline Schneider, Hanz Hartmann Maize as energy crop for combustion. Agricultural optimization of fuel supply. TFZ, 2006. http://www.tfz.bayern.de/mam/cms08/festbrennstoffe/dateien/09_bericht.pdf*
[19] *Characterisation of Agricultural Waste Co- and By-Products. Report of the AgroCycle project. 2016. http://www.agrocycle.eu/files/2017/10/D1.2_AgroCycle.pdf*
[20] *Vladislav Zekić, Vesna Rodić, Milenko Jovanović Potentials and economic viability of small grain residue use as a source of energy in Serbia. Biomass and Bioenergy, 2010. DOI: 10.1016/j.biombioe.2010.07.012*

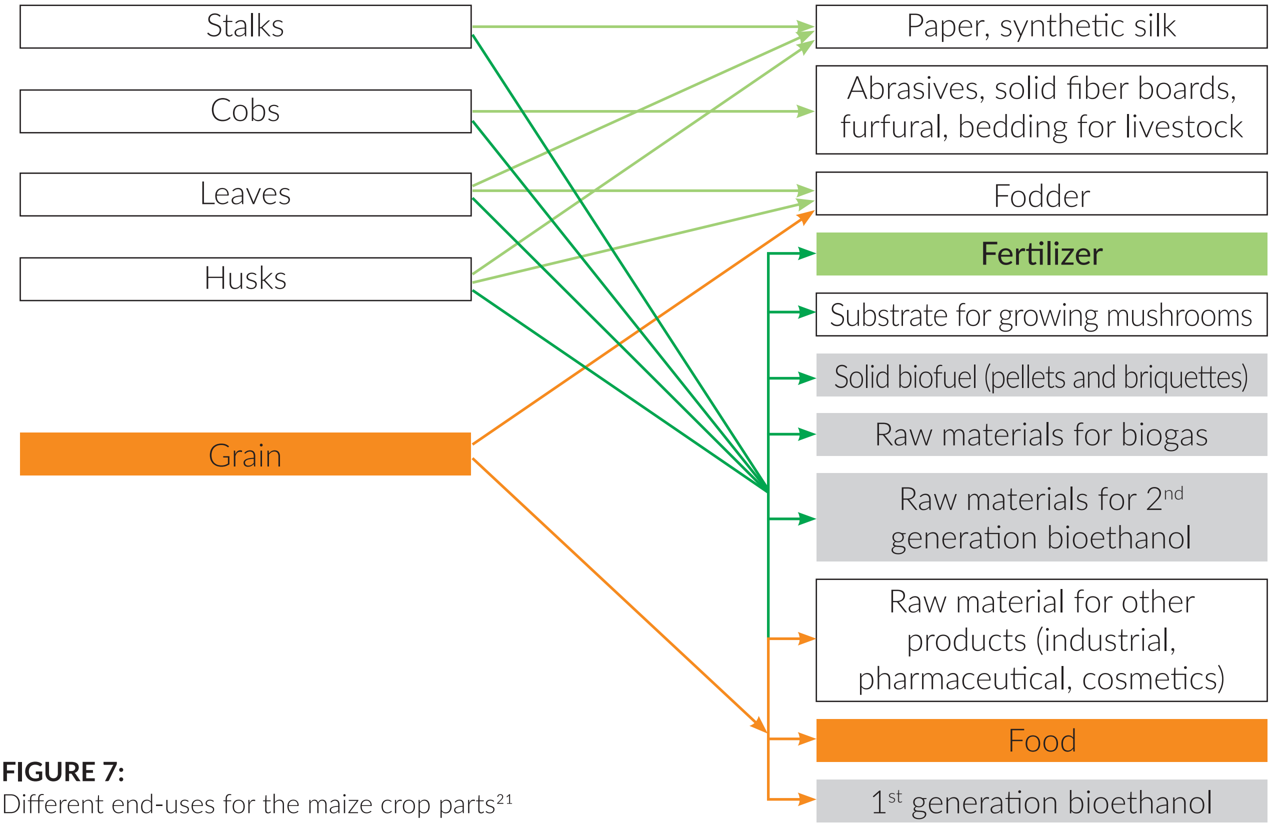

FIGURE 7:
Different end-uses for the maize crop parts[21]

[21] *Position paper UABIO N 23 (2020) "Analysis of pellets and briquettes production from corn residues" https://uabio.org/wp-content/uploads/2018/05/position-paper-uabio-20-en.pdf*

FUEL PROPERTIES OF MAIZE RESIDUES

Generally speaking, maize residues have tricky fuel properties for combustion, which, however, are better than those of cereal straw. In any case, when choosing a boiler for maize residues, the actual fuel characteristics of the supplied corn stover and the requirements of boiler manufacturers should be taken into account. A comparison of fuel properties of maize residues with those for other agricultural residues and wood chips is shown in Table 2.

TABLE 2:
Comparison of indicative fuel properties of maize residue fractions with different biomass assortments.

Parameters	Units	Yellow straw[1]	Gray straw[1]	Corn cobs[2]	Maize stalks[3]	Wood chips[1]
Moisture content	%	10-20	10-20	12.5	10-18	40-50
Net calorific value	MJ/kg	14.4	15	15.2	15-17	10.4
Ash content	%wt	4	3	2.2	5-6.5	1
Carbon	%wt	42	43	41.3	41	50
Hydrogen	%wt	5	5	5.2	5.1	6
Oxygen	%wt	37	38	38.8	38	38
Chlorine	%wt	0.75	0.2	0.14	0.13	0.02
Nitrogen	%wt	0.35	0.41	0.5	0.84	0.3
Sulphur	%wt	0.16	0.13	0.08	0.09	0.05
Potassium (alkali metal)	%wt dry	1.03*	0.61**	0.48-1.02	0.61	0.14***
Ash deformation temperature	°C	930*	905**	790-1200 (1033 mean value)	820-1160 (1070 mean value)	1270***

[1] Straw to Energy. Technologies, policy and innovation in Denmark. Second edition" (http://agrobioheat.eu/wp-content/uploads/2020/11/AgroBioHeat_D7.6_Straw_to_energy_EN.pdf).
[2] Aggregated data from the Phyllis database (https://phyllis.nl/); Brunner et al., 2011[22]; Brunner et al., 2021[23]; Antonenko et al., 2018[24]; AgroCycle. Characterisation of Agricultural Waste Co- and By-Products http://www.agrocycle.eu/files/2017/10/D1.2_AgroCycle.pdf.
[3] Aggregated data from the Phyllis database (https://phyllis.nl/); Antonenko et al., 2018[24]; AgroCycle. Characterisation of Agricultural Waste Co- and By-Products http://www.agrocycle.eu/files/2017/10/D1.2_AgroCycle.pdf
* Mean value for wheat straw (Danish) from the Phyllis database (https://phyllis.nl/).
** Mean value for wheat straw (Danish, weathered) from the Phyllis database (https://phyllis.nl/).
*** Mean value for untreated wood from the Phyllis database (https://phyllis.nl/).

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[22] *Brunner, T., Kanzian, W., Obernberger, I., & Theissl, A. (2011). Combustion properties of maize cobs – results from lab and pilot-scale tests. In Proceedings of the 19th European Biomass Conference & Exhibition (pp. 944-951).*
[23] *Brunner, T., Nowak, P., Mandl, C., Obernberger, I. (2021). Assessment of agrobiomass performance in state-of-the-art residential boilers. In Proceedings of the 29th European Biomass Conference & Exhibition (pp. 379-388).*
[24] *V.O. Antonenko, V.I. Zubenko, O.V. Epik Fuel properties of Ukrainian corn stover. DOI https://doi.org/10.31472/ihe.3.2018.11*

The elemental composition of maize residues is almost the same as for straw of spiked cereal crops, so they have a comparable calorific value. The properties of straw strongly depend on the place of cultivation, harvesting time and weather, soil, and fertilizers[25].

The ash content of corn stover is a significant quality factor for further production of biofuels. The ash content depends on the type of harvesting technology as the amount of ash increases when biomass contacts with soil. Because of this, there are two types of ash: structural and non-structural[26]. Structural ash consists of inorganic substances contained in the plant biomass. The usual structural ash content of corn stover is 3.5%. Non-structural ash is an inorganic substance (mostly soil) that gets into straw during harvesting, in particular when forming swaths and baling. Typical total ash content for multiple passes of agricultural machines when harvesting is 8-10%.

As for ash melting behavior, some samples of maize residues are closer to wood biomass, which provides better conditions for combustion compared to the straw of spiked cereal crops. For comparison: the ash deformation temperature for wood is about 1270 °C, and that is 790-1200 °C for corn cobs and 820-1160 °C for maize stalks (see Table 2). In addition, maize stalks contain less chlorine (0.13%) as compared to the fresh ("yellow") straw of spiked cereal crops (0.75%). It is a positive factor for maize residues as fuel because chlorine compounds cause corrosion of steel elements of energy equipment.

The moisture content has a crucial influence on the calorific value of maize residues. The diagram of dependence of the net calorific value of the moisture content of corn stover, which is built on the equation (2.2) from the handbook[27], is shown in Fig. 8.

For achieving a relatively low moisture content of maize by-products, it is essential to choose an appropriate harvesting and logistic strategy.

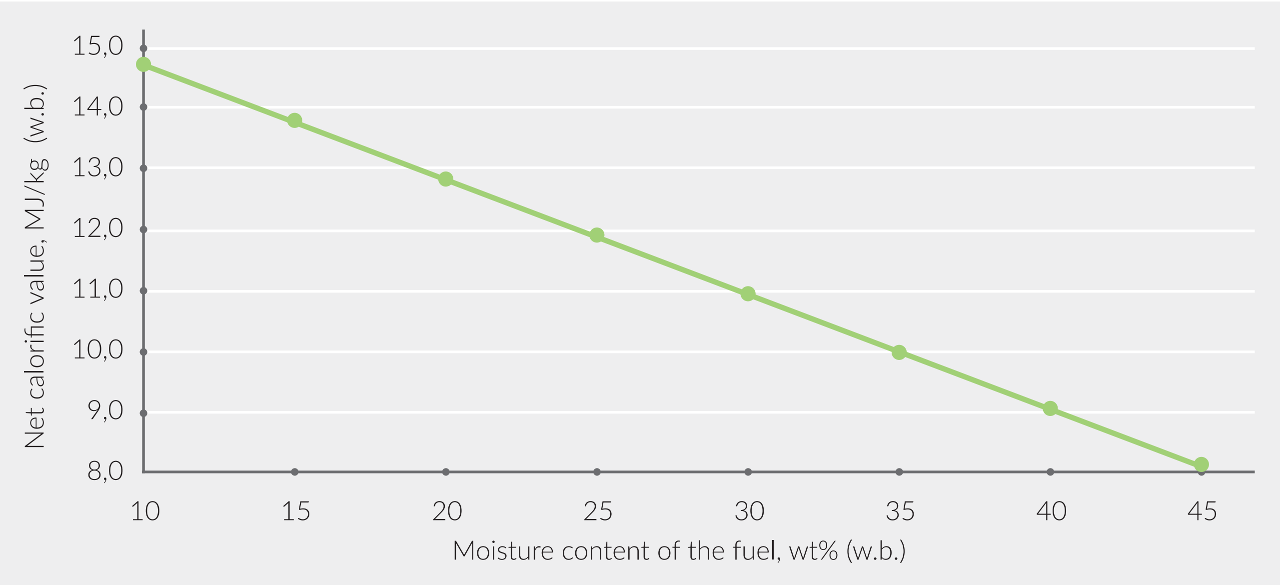


FIGURE 8:
Net calorific value as a function of moisture content (w.b.) of corn stover.

[25] *Vyll Varesa. Handbook for biofuel consumer // Tallinn: Tallinn Technology University, 2005 – 183 p.*
[26] *Brittany Schon, Matt Darr. Corn Stover Ash. https://store.extension.iastate.edu/Product/Corn-Stover-Ash*
[27] *Van Loo, S.; Koppejan, J. The Handbook of Biomass Combustion and Co-firing; Earthscan: London, UK, 2008. – 465 p.*

HARVESTING OF MAIZE RESIDUES

MAIZE GRAIN HARVESTING TECHNOLOGIES

The maize grain harvesting technology has a direct impact on the types of maize residues that can be obtained and the way they can be collected. There are three main technological schemes for harvesting grain maize (Fig.9):

1. Harvesting grain maize with corn combines with the further stationary treatment of ears:
   1.1. with simultaneous peeling of ears (separation of wrap);
   1.2. without peeling of ears;
2. Harvesting grain maize with combine harvesters equipped with corn headers;
3. Collection of a mixture of grain and cobs with combines.

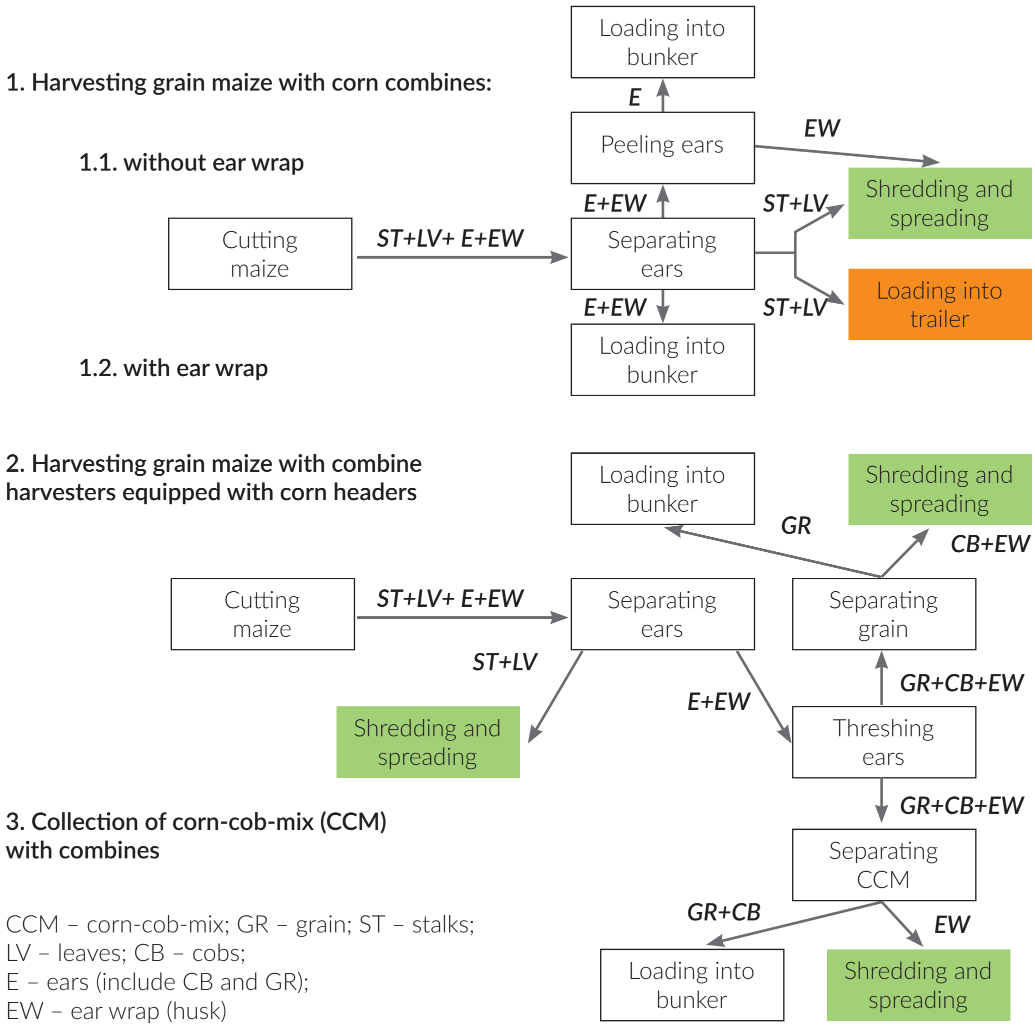


FIGURE 9:
Grain maize harvesting technologies with maize residues streams[28]

[28] UABio's Position Paper N 16 (2016) "Opportunities for harvesting by-products of grain corn for energy production in Ukraine" http://uabio.org/img/files/docs/position-paper-uabio-16-en.pdf

FIGURE 10:
Harvesting of corn with the combine harvester equipped with a corn header.

Maize grain should be harvested with the grain moisture content of 20 to 35-40%, while corn-cob-mix should be harvested when the grain moisture content is 40-50%. Corn harvest without cobs thrashing starts when grain moisture is less than 40%, with cobs threshing – with less than 30%. With higher moisture content threshing worsens, corn injures, harvesters productivity reduces. The best quality thrashing takes place when the grain moisture is 20-22%[29].

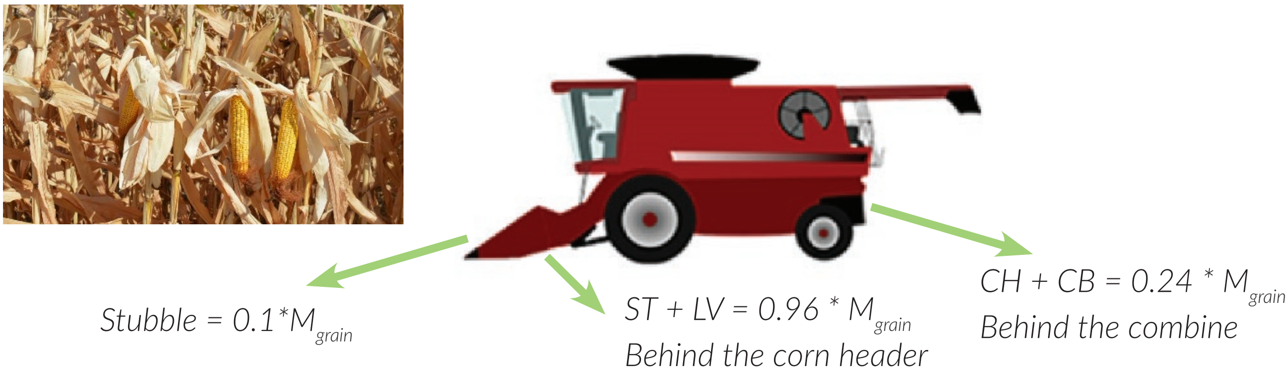
In Ukraine, in the 1980s-1990s, maize grain harvesting technology was popular, which included the collection of all biological yield of the crop through the use of combine harvesters SK-5M, Enisei-1200, Don-1500, and KZS-9-1 with special headers PPK-4, KMD-6, PZKS-6 produced by "Khersonmash" plant. These headers transmitted shredded corn stover to the trailer.

Currently, the main method for harvesting commercial grain maize is a combine threshing of ears in the field, shredding, and spreading of the cut biomass with the use of combine harvesters equipped with corn headers (Fig. 10). This method of grain maize harvesting is the most economically feasible. In comparison with harvesting ears, the method provides a 1.8-2 times decrease in labour costs and 20-25% reduction in fuel consumption[30]. Only some farmers (mainly seed factories) collect corn as non-threshed ears with the following stationary threshing, which makes it possible to collect cobs. The seed factories grow maize to obtain (hybrid) corn seeds as planting stock. As compared to the EU, the collection of corn-cob-mix with combines is not widespread in Ukraine yet.

[29] *V.D. Hrechkosii, M.D. Dmytryshak, R.V. Shatrov and other. Complex mechanization of grain production: Textbook // K: Ltd. "Nilan-Ltd", 2012 – 288 p.*
[30] *Cherenkov A.V., Tsykov V.S., Dziubetskyi B.V., Shevchenko M.S. et al. Intensification of corn technologies – a guarantee for yield stabilization at 90-100 m.c./ha level (practical recommendations) // Dnepropetrovsk: NU Institute of Steppe zone agriculture NAASU, 2012 – 31 p.*

HARVESTING OPTIONS FOR MAIZE RESIDUES

When harvesting grain with a combine harvester equipped with a corn header, the plant remains are redistributed as follows (Fig. 11): stubble remains (10% of the grain weight), remains behind the corn header (96% of the grain weight), and remains behind the combine harvester (24% of the grain weight). It should be noted that corn headers require much more power than grain headers. Typically, it is 7.5 kW (10 HP) per row and extra power 2.3 kW (3 HP) per row is demanded at the header if stalk-shredding attachments are installed[31].



ST – stalks, LV – leaves, EW – ear wrap (husk), CB – cob, M_{grain} – weight of grain

FIGURE 11:
Formation of maize residues behind the combine harvester.

Pressing biomass into bales due to raw materials compacting in more than 4 times (from 40 kg/m³ to above 160 kg/m³) contributes to increased logistics efficiency and reduces the required area of storages. Technological schemes for harvesting maize residues can be divided into 4 main types for bales:

1. Single-pass harvesting system: a baler is attached to a combine harvester that allows forming maize by-products bales at the same time as the grain threshing (Fig. 12a).

2. Two-pass system: a combine harvester with a corn header that forms a maize windrow, which is then baled with a baler attached to a tractor (Fig. 12b).

3. Three-pass system: combine harvester + tractor with stalk-shredding windrower + tractor with baler of large square bales (round bales) (Fig. 12c).

4. Multi-pass system: combine harvester + tractor with mulcher + tractor with rake + tractor with baler (Fig. 12d).

Typical corn stover harvested in a multi-pass method will result in the ash content levels between 8 and 12% depending on the year and crop conditions and mainly consists of soil contamination collected during the baling process. Single-pass harvesting produces corn stover feedstock with the ash content of less than 4% and never allows the feedstock to reach the ground until a bale is formed (Fig. 12a). Single-pass combines have harvesting productivity loss because of additional biomass flow through them. Combines designed to handle higher rates of biomass have a 30% reduction in productivity at 3.4 Mg/ha biomass collection rates[32]. AGCO corporation produces Challenger single-pass harvesting system, which is available on the market of some countries including the USA.

[31] Corn: Chemistry and Technology, Third Edition. Edited by Sergio O. Serna-Saldivar Woodhead Publishing and AACC International Press, 2018. – 690 p.
[32] J. Darr, K. Webster, A. Shah Machinery Innovations to Meet Industrial Biomass Harvesting Demands in Expanding United States Markets / Land.Technik AgEng 2013. Conference Proceedings, 2013. – 399-406 p.

a) Single-pass harvesting system: combine with baler

b) Combine with windrowing header + tractor with baler

c) Combine + tractor with stalk-shredding windrower + tractor with baler

d) Combine + tractor with stalk-shredder + tractor with rake + tractor with baler

FIGURE 12:
Technological schemes for corn stover harvesting[33].

For efficient maize by-products collection and baling, it is important to make windrow from maize residues. In the two-pass system, a combine harvester with a special corn header that forms a maize residue windrow is used (Fig. 12b). The Geringhoff Mais Star Collect corn header can shred and spread maize leaves and stalks on a field or put them into the windrow. On top of the windrow also can be added shredded cobs and husks that are formed after the combine shredder. New Holland company produces devices – Cornrower™ for forming windrows, that can be attached to combine. Comparative field tests of single- and two-pass corn stover harvesting[34] showed that the grain harvest productivity of the two-pass systems was 9% lower than that of the conventional combine configuration. Also, for these two harvesting technologies, farmers have to invest in special equipment (single-pass harvesting system or corn headers), which will reduce the productivity of maize grain harvesting.

[33] Report on "Analysis of utilisation of corn straw as an energy source" (2018). Prepared by SEC Biomass for EBRD under the Contract C38842/1018/5362.
[34] K. J. Shinners, R. G. Bennett, D. S. Hoffman Single- and two-pass corn grain and stover harvesting Transactions of the ASABE. 55(2): 341-350. (doi: 10.13031/2013.41372) @2012
https://elibrary.asabe.org/login.asp?search=0&JID=3&AID=41372&CID=t2012&v=55&i=2&T=2

Usually, farmers do not have the necessary resources to provide harvesting of biomass, because they are aimed to produce maize grain. Farmers tend to harvest maize grain with standard combine harvesters and corn headers without increasing harvesting campaign terms. For effective maize residues harvesting, it is better to engage a particular company, which has special efficient machinery and collects agrobiomass with good quality. It can be achieved in three-pass and multi-pass systems.

In the three-pass system, the special shredder, stalk-shredding windrower (Fig. 12c), is used for maize residue shredding and windrowing. In this case, the combine harvester can increase its performance during maize grain harvesting. The USA company, Hiniker, produces 5600 series machines with a width of 15, 20, and 30 feet for crop residues shredding and windrowing. To ensure the high linear weight of the windrower and to reduce the number of machinery passes, Hiniker 5610 and 5620 are connected two passes in a single windrower. The shredder with a width of 30 feet must be attached to a tractor with 200 hp engine power.

In a multi-pass system, a shredder attached to a tractor for shredding of maize residues, which are raked by rake attached to the tractor in windrowers at the next step, is used (Fig. 12d). To operate with corn stalks, the rake must be equipped with stronger fingers compared to a hay rake. Like rakes, the harvest yield from stalk shredders can be adjusted by changing the clearance between the shredding knives and the ground. Because the stalk shredders have less opportunity to engage the soil, the soil contamination or ash level of corn stover produced with a stalk-shredding windrower is generally less than with a raked windrow[35].

To prevent dry matter losses and biomass quality deterioration, bales must be quickly taken off a field and put in piles for storage. For example, a self-loaded trailer 16K Plus Bale Runner collects 12 large bales with 1.2 m width and 0.9 m height in one pass and is mounted on a tractor with 180 hp power. In the USA, also special self-propelled stackers are used. Stinger Stacker 6500 machine has an engine capacity of 305 hp, 6-speed automatic transmission and during 1 hour can pick up, take out, and put in a pile 80-120 large rectangular bales.

Of these technologies, the three-pass system (Fig. 12c) is more applicable for European conditions due to the possibility of the use of standard machinery available for agricultural producers and less biomass contact with the soil. At different stages of the harvesting process, different models of equipment can be used. Some examples of such machinery are shown in Fig. 13. More information about machinery for harvesting, logistics maize residues, and processing them into pellets/briquettes is included in Annex I.

Used in the USA	EU analogs
1. Windrowing	
Hiniker 5600 series	Biochipper 300, 400, 500, 600
2. Baling	
Massey Ferguson 2270XD	Krone Big Pack 1290 HDP
3. Collection of bales in a field	
ProAg 16 K Plus Bale Runner	Arcusin Autostack XP 54T

FIGURE 13:
Models of farm machinery for maize by-products harvesting.

[35] *Matt Darr Industrial harvesting of corn stover as a biomass (2012). Proceedings of the Integrated Crop Management Conference. 9. https://lib.dr.iastate.edu/icm/2012/proceedings/9*

THE DUPONT CORN STOVER SUPPLY CHAIN

An example of the whole supply chain of maize residues (baled biomass) is presented in Fig. 14. It was the supply chain implemented and used by the DuPont company (the USA) to provide its cellulosic ethanol plant with feedstock. On October 30, 2015, the large advanced biorefinery of the Dupont was opened in Nevada city, Iowa State. The capacity of the plant was more than 110 mln litres of cellulosic ethanol per year. Corn was harvested by local farmers while other operations were carried out by the plant staff. In 2018, Verbio North America Corp. purchased the DuPont Cellulosic Ethanol LLC in Nevada. The new owner has plans to produce renewable natural gas (RNG) at the site but first will need to make some changes to the facility[36].

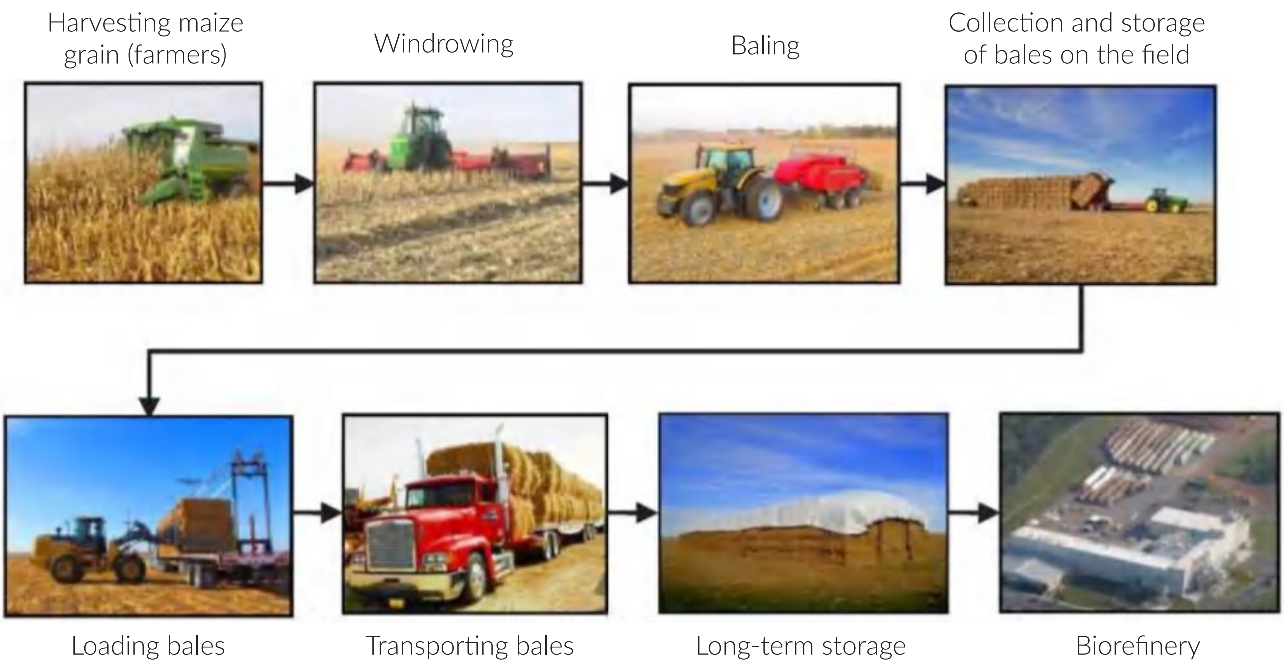


FIGURE 14:
DuPont's cellulosic ethanol plant model for corn stover supply chain[37].

[36] http://ethanolproducer.com/articles/15885/burgeoning-biomethane
[37] DuPont Nevada Site Cellulosic Ethanol Facility Feedstock Collection Program http://www.dupont.com/content/dam/dupont/products-and-services/industrial-biotechnology/documents/IB-PDF-04-Feedstock_Collection_Program_2015.pdf

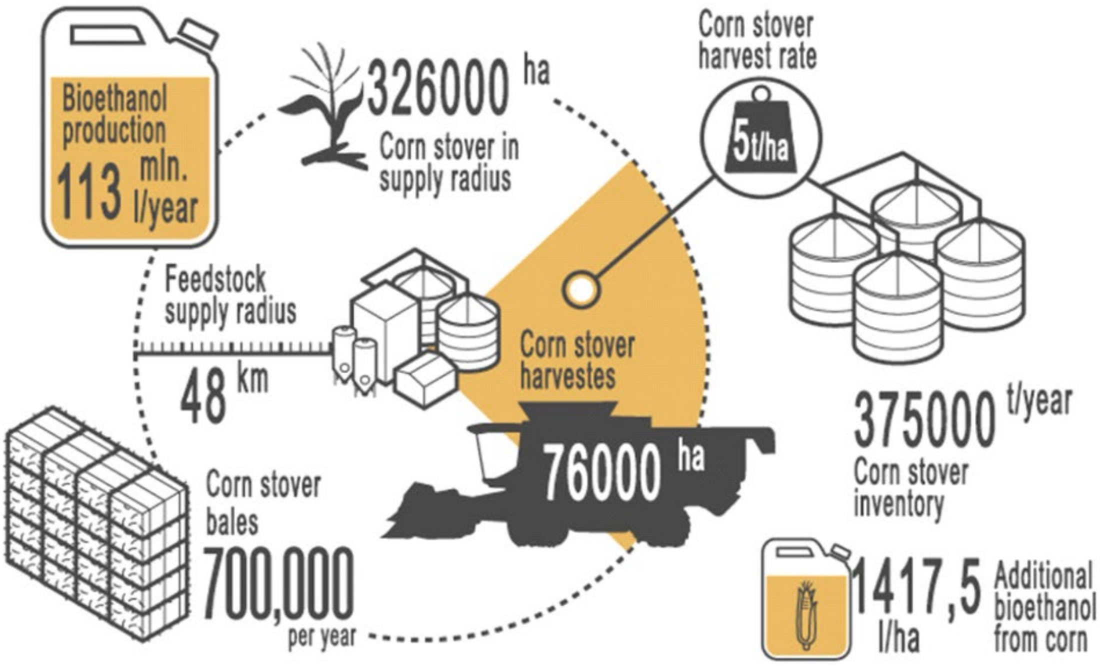


FIGURE 15:
Operation program of DuPont cellulosic bioethanol plant[38]

The operation program is shown in Fig. 15. The DuPont plant was paying growers for the permission to harvest corn stover and manage the costs of harvesting, storage, and transportation. Growers got costs for giving access to the field and for the amounts of nutrients that were removed together with the maize by-products. Corn stover was harvested from the 500 nearest farms. There were 85 permanent jobs at the plant, and 150 individuals were involved in the collection, transportation, and storage of seasonal feedstock collection.

Due to the DuPont cellulosic ethanol corn stover harvest program, DuPont was contracting with growers to harvest, store and deliver corn stover to the DuPont cellulosic ethanol plant. Qualified growers had to meet the following criteria:
• Located within a 48 km radius of Nevada, Iowa;
• Corn acres must be grown in a no-till or conservation tillage system;
• Yield of 12.2 tons per ha or higher;
• Relatively flat land (with a slope of 4% or less).

TRANSPORTATION OF CORN STOVER BALES

Also, similar to described above, the maize by-products harvesting system in large square bales is used by other companies. After stacking the bales on the operative warehouses near fields, they should be transported to the main (central) warehouse. For loading operations in warehouses, frontal loaders and telehandlers are used. For transportation from the local to the central warehouse, trucks with semi-trailer platforms are used. Such equipment is traditionally used for logistic operations with bales of straw and hay. But bales from maize by-products generally have a higher moisture content and, therefore, they are heavier compared to bales from cereals straw and oilseed rape, so this should be considered when choosing machines for bales picking up and stacking. It is essential to secure cargo properly using tiedown or ratchet straps on flatbed trailers or trailers without sides[39]. Up to 36 large square bales with an average dry weight of 0.43 t can be transported on a standard USA 48-ft semi-trailer. Dry bale density of 196 kg/m³ should be targeted to

[38] http://www.dupont.com/products-and-services/industrial-biotechnology/advanced-biofuels/articles/nevada-cellulosic-ethanol-by-the-numbers.html
[39] Justin McGill, Matt Darr Transporting Biomass on Iowa Roadways. PM 3051G (2014) https://store.extension.iastate.edu/product/Transporting-Biomass-on-Iowa-Roadways

maximize the transportation weight hauling efficiency of standard semi-trailers. Biomass loads should be properly secured to ensure loads do not shift during transportation.

HARVESTING OF CORN STOVER IN ROUND BALES

Furthermore, the biomass can be baled in round bales using a round baler instead of a large square baler. Round balers are also very viable for biomass production and offer the benefit of being simpler to operate with fewer maintenance challenges[40]. Round balers can require up to 75 PTO horsepower. For adequate drawbar power and to maximize the productivity of the baler, it is recommended that a tractor with 120+ horsepower be used for industrial baling operations. High-density round balers with chopping pretreatment can achieve bale densities of 160 kg/m^3. Large square balers require considerably more power than round balers. High-density and high-capacity large square balers typically list a minimum of 180+ horsepower in the manufacturer's literature. Additional horsepower may be required if high-density balers are used. Such balers can produce bales of over 184 kg/m^3 density. But in general, the round balers are less productive than large square balers. Considering the smaller volume efficiency of transportation and storage, logistics operations of the round bales in comparison with square bales, round bales are more complex and more expensive.

HARVESTING OF SHREDDED CORN STOVER

In addition to the baling technologies, corn stover can be harvested in shredding form as a mixture of different fractions of maize by-products or separate from them, such as cobs. The flow charts of shredded maize residues harvesting with the use of a forage harvester or a forage loader wagon, which are used for silage corn harvesting, are shown in Fig. 16. Field experiments in the Bavarian State Research Centre for Agriculture in 2014 and 2015 show that the ash content of corn stover was 7.0 % in DM ±1.9 for forage harvester and 6.9% in DM ± 2.0 for forage loader wagon[41].

a) Forage harvester system:
combine + tractor with stalk-shredding windrower + forage harvester + tractor with trailer

b) Forage loader wagon system:
combine + tractor with stalk-shredding windrower + tractor with forage loader wagon

FIGURE 16:
Shredded corn stover supply chains

[40] *Matt Darr, Keith Webster Corn Stover Harvesting Machinery. PM3051A (2014) https://store.extension.iastate.edu/product/Corn-Stover-Harvesting-Machinery*
[41] *Monika Fleschhut, Kurt-Jurgen Hulsbergen, Stefan Thurner, Joachim Eder Analysis of different corn stover harvest systems / LANDTECHNIK, 71 (6), 2016. – 252-270 p.*

HARVESTING SYSTEMS FOR MAIZE COBS

Another option for the harvesting of maize residues is to collect a part of them after threshing grain in a combine harvester. In 2018, researchers at Italian CREA-IT (Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria) have carried out on-field trials in the BECOOL project to assess the performance of an innovative mechanized system, called Harcob, to collect maize cob[42] (Fig. 17a). Using the combine harvester with the Harcob system, it was possible to harvest 2 t/ha of cobs in the average (4.1 t/hour)[43]. The Vermeer Company releases a cob harvester machine CCX770 (Fig. 17b), which is available on the market[44]. The Vermeer CCX770 cob harvester is a pull-type cob collection wagon attached to a combine harvester. This machinery enables farmers to harvest both corn and cobs – separately and simultaneously – in one pass.

In Ukraine, some farmers adjust the separation system of the combine harvesters to reduce the separation of maize grain from cobs. This way, grain with cobs is transferred to the grain bunker. Then, this mixture is separated on stationary separation units, and cobs are used as biomass for maize grain dryers. The described technology is based on existing machinery and does not need capital expenditure for additional equipment. But, it is used only to cover farmers' own needs and does not apply for largescale collection of this type of biomass for the bioenergy sector.

a)

b)

FIGURE 17:
Cob harvesters: a) Harcob system; b) Vermeer CCX770.

CORN STOVER STORAGE

The corn stover should be stored under the conditions of keeping its normal level of moisture content because of rains and soaking from the ground, avoiding decay, and ensuring protection against fire. The selection of a storage type depends on its location and local conditions. The corn stover can be stored in open storage, tarped storage, permanent structure storage, or anaerobic storage[45]. Several factors should be considered when selecting appropriate storage systems: feedstock stability during storage, cost of storage infrastructure, accessibility of feedstock during the entire storage duration, integration of storage platform with a processing plant. It is important to secure free access to biomass for the loaders.

The storage of biomass in permanent structures offers many advantages in comparison with other systems. However, due to the relatively low density of corn stover, including bales and high capital costs for new storages building, the permanent storages are eco-

[42] https://www.becoolproject.eu/2018/10/22/recovering-maize-cob-converting-untapped-biomass-resource-into-valuable-feedstock/
[43] http://www.etaflorence.it/proceedings/?detail=15215
[44] https://www.vermeer.com/NA/en/N/equipment/cob_harvester
[45] Matt Darr, Ajay Shah, Kevin Peyton, Keith Webster Corn Stover Storage Methods https://store.extension.iastate.edu/product/14077

FIGURE 18:
Open-air storage of corn stover bales in Spain

nomically unfeasible. In this case, if a stakeholder has permanent storages, he can use them for corn stover.

Open-air storage can be used for temporary local storages of corn stover when the upper layer of biomass serves as coverage (Fig. 18). Also, it can be used for the main storage facility in some regions, but it is necessary to do this very carefully because of biomass dry matter losses.

Anaerobic storage or ensiling is a widespread storage method for wet feedstocks in the livestock industry. Anaerobic storage remains economically viable for high moisture feedstocks, particularly for early season bale storage or for emergency storage during extremely wet harvest seasons[45].

The tarped storage of corn stover offers the optimal balance of cost and quality preservation. Agrofibre material can be used as tarp material, which provides rain and snow protection. It gives a possibility of air out through it, which prevents the formation of fungus and mould. The agrofibre is used for wood chips drying. The agrofibre can be used for more than 5 years[46].

The corn stover storage facilities have to be arranged according to the Fire Safety Regulations. For instance, in Ukraine[47], the area of one stack of straw bales must be less than 500 m², and shredded straw must be less than 300 m². It is allowed to dispose of bales (shredded straw) in double stacks with a distance not less than 6 m between stacks in pair and not less than 30 m between adjacent double stacks.

[45] Matt Darr, Ajay Shah, Kevin Peyton, Keith Webster Corn Stover Storage Methods https://store.extension.iastate.edu/product/14077
[46] http://zavod-kobzarenko.derevo.ua/catalog/details/6019
[47] http://zakon.rada.gov.ua/laws/show/z0313-07

DENSIFICATION OF MAIZE RESIDUES

Further processing of maize by-products into briquettes and pellets will increase the added value of biomass. Biomass briquettes are pressed materials of cylindrical, rectangular, or any other shape with a cross dimension that is not less than 25 mm and with a length of 100-400 mm. The typical diameter of a briquette is 60-75 mm, and its length usually is within five diameters. There are no standard sizes for this product. Briquettes may be of very different shapes, but on the whole, three types can be distinguished: NESTRO, RUF, and Pini&Kay (the names are based on the names of companies that manufacture well-known presses for the production of briquettes of these types). A typical process of biomass briquettes production includes seven stages: receiving of feedstock, shredding, calibration, drying, pressing of feedstock into briquettes (briquetting), cooling, and packing of briquettes. Obtaining a strong briquette from the shredded plant mass is ensured by both physical and mechanical properties of the material and conditions of the briquetting process itself. At that, certain quality levels must be achieved. They are the briquette density (0.8-1.3 t/m^3), moisture content, dimensions (diameter, length), and regular shape. Density is the main factor that determines the mechanical strength and water resistance of a briquette. An important advantage of briquettes as fuel is the constant temperature during combustion for several hours. Biomass briquettes can be combusted in domestic boilers and small boilers for solid fuels with manual loading (up to ~100-150 kW), which often are already available in households, state-financed institutions, or institutions of the social sphere. In the market, there are also automated boilers with bunkers (up to ~240 kW) designed for biomass briquettes. Briquettes of lower density (that is «softer» due to pressing of wetter feedstock) can be used in large boilers with screw feeding. It is expected that the screw manufactured of strong metal will be able to crush briquettes and ensure their uninterrupted feeding into the furnace.

Agricultural biomass is pelletized to increase the efficiency of logistic operations and expand the possibility of its energy use. Pellets from maize residues are referred to non-woody pellets, and the technical process of their production is similar to biomass briquetting related to the feedstock characteristics. Non-woody pellets are densified biofuel made from grinded or milled biomass with or without additives. They have a shape of cylinders with diameter < 25 mm, random length (typically 3.15 to 40 mm), with broken ends, obtained by mechanical compression[48]. The main characteristics that affect the organization of the production process of granulation are the initial condition of the biomass (particle size, initial volume reduction, presence of impurities, moisture content). When processing crop residues, sunflower husks, reeds, etc. it is possible to use a typical scheme designed for the production of straw pellets.

To summarize, many technologies based on different machinery can be applied for maize by-product harvesting. For large-scale harvesting, it is reasonable to use special high productivity machinery, including, stalk-shredding windrower, balers, trailers, etc. But, for small-scale harvesting, it can be done in different ways based on the existing equipment. It is important to reduce the contamination of biomass with soil and prevent the high moisture content of maize by-products. The main cost elements of corn stover tarped storage are land rent costs, ground preparation costs, tarped material, loading/unloading costs, guard costs, and costs related to feedstock losses because of biomass dry matter loss. The corn stover processing into briquettes and pellets increases the energy density of the biomass volume, which is especially important when transporting biomass over long distances.

[48] *ISO 17225-6:2014 Solid biofuels – Fuel specifications and classes – Part 6: Graded non-woody pellets*

HEAT PRODUCTION FROM MAIZE RESIDUES

HEAT PRODUCTION FROM MAIZE STRAW

Maize residues like other types of crop residues were used for space heating in rural areas with cold winter, especially on the territories with a lack of forests. For example, in southern villages of Odesa region in Ukraine for decades locals have been used a practice, when they rent plots of maize fields from agricultural enterprises or farmers. Then the locals cultivated and harvested maize manually, but nowadays they use machinery, including, balers for corn stover. They collect maize residues and put them near their houses (Fig. 19). In the cold period, the locals use the maize residues as fodder and biomass for heating. They burn corn stover in traditional stoves, the usage of which is reducing last years.

Shredded corn stover is difficult biomass for small-scale domestic heating usage due to its low density. Also, handling of large bales can be a problem. In this case, the production of briquettes and pellets from such biomass can be an option for modern boilers. However, for now, the wide production of solid biofuels from maize residues is not launched in Ukraine and Europe. There are only a few cases of heat generators on corn stover bales, which are used for heating and grain drying. The main reason for this is the problem with the harvesting of biomass during rainy weather and contamination of it with soil under windrowing.

FIGURE 19:
Corn stover square bales in the village of Krynychne.

As mentioned above the maize residue can be considered as better biomass for combustion compared to cereal straw, but the fuel characteristics of agrobiomass depend on many local conditions and harvesting practices. In any case, boilers must fit for burning the maize residues. This can be as enhanced boiler for burning of wood biomass as a specially designed boiler. In general, cereal straw boilers can be considered as suitable for corn stover, provided it has a suitably low moisture content upon combustion. Also, it can be used heating solutions for the combustion mix of biomass, for example, wood with maize residues.

The experiments of small corn stover bales combustion in a 146 kW boiler with dual chambers designed for wood logs without any modification and combustion of round corn stover bales in the batch-fed fired biomass boiler Farm 2000 with a rated output power of 176 kW are described in the articles[49,50]. Both of the boilers had shown good potential for heat production using corn stover bales, but these boilers needed improvement for more effective combustion. Thus, in the small-scale 146 kW boiler, corn stover bales produced on average 7.5% ash, which included about 2% of unburned residues while wood produced 1.7% ash. Flue gas emissions averaged 1324 mg/m^3 CO and 99.1 NOx for stover (118 mg/m^3 CO and 50.6 NOx for wood). The overall heat transfer efficiency for stover was lower than for wood (57% vs. 77%). And, in the batch-fed fired biomass boiler, average emissions from corn stover were 2725 mg/m^3 CO, 9.8 mg/m^3 NOx, and 2.1 mg/m^3 SO_2, which were lower concerning NOx and SO_2 and higher concerning CO than emissions from wheat straw (CO 2210 mg/m^3, NOx 40.4 mg/m^3, and SO_2 3.7 mg/m^3).

It should be noted that both of the boilers used a fixed grate combustion systems, which often exhibit low efficiencies and high emissions of unburnt pollutants for combustion of agrobiomass with high ash content. Moving grate systems can achieve a higher combustion velocity and efficiency, compared to fixed grate ones, because the solid fuel moves across the grate from the inlet section to the ash discharge section and this allows a better mixing between air and fuel and facilitates the distribution of char, which then burns more quickly[51].

Interest in the use of maize straw for heating applications can be found in territories that intend to phase-out coal for heating and have a high potential of this resource. In Greece, the Municipal District Heating Company of Amyntaio (DETEPA) in West Macedonia inaugurated in autumn 2020 a new biomass heating plant (2 x 15 MW) for substituting the heat supplied by a now decommissioned lignite fired power plant. In its first year, the plant was relying more on biomass feedstocks that could be sourced from established producers (wood chips and sunflower husk pellets), but DETEPA has a keen interest to develop local agrobiomass supply chains, aiming to procure around 5,000 tons of maize straw and vineyard prunings in the 2021-2022 heating season[52]. In China, there is a huge potential of agricultural residues – including maize straw. The company Great Resources has developed different projects for utilizing maize straw, from grain drying plants using maize straw briquettes to multi-generation plants producing cooling, heat, steam, electricity and fertilizer from maize straw[53].

HEAT PRODUCTION FROM CORN COBS

At a first glance, the fuel properties of corn cobs appear quite promising: lower ash and nitrogen content compared to many other agrobiomass fuels. The main challenge in corn cob combustion is the high potassium content of the fuel, which lowers the ash melting temperature. Molten slags may form on the grate of the furnace, obstructing the air passages. In addition, ash deposits on heat exchange surfaces are very insulating and may lead to considerable efficiency losses due to decreased heat transfer. Finally, corn cobs typically exhibit a high chlorine content which – in combination with potassium and other compounds – may lead to the formation of corrosive substances. Results of corn cob combustion in the lab-scale reactor and

[49] R.Morissette, P.Savoie, J.Villeneuve Combustion of Corn Stover Bales in a Small 146-kW Boiler // Energies, 2011, 4. – 1102-1111 p.
[50] R.Morissette, P. Savoie, J. Villeneuve. Corn Stover and Wheat Straw Combustion in a 176-kW Boiler Adapted for Round Bales // Energies, 2013, 6. – 5760-5774 p.
[51] https://agrobioheat.eu/wp-content/uploads/2020/10/AgroBioHeat_D4.2_agrobiomass-fuels-and-utilization-systems_v1.0.pdf
[52] www.ot.gr/2021/10/05/english-edition/kozani-green-heating-from-corn-and-vine-residues/
[53] Hong Hao Unlock the huge potential of agro residue. Presentation. 9.12.2021 https://www.worldbioenergy.org/news/574/50/WBA-Webinar-1-Agricultural-residues-to-energy/

pilot-scale grate-fired biomass combustion plant in Austria are described in the paper[22]. The energy density of maize cobs amounts to 518 kWh/m³ (about 55% of the energy density of wood chips with comparable moisture content). Due to the higher N content of maize cobs compared to chemically untreated wood chips increased NOx emissions have to be expected. During the pilot-scale test runs the combustion plant has been operated at 70 to 85% of its nominal boiler capacity (350 kW_{th}). The formation of small slag pieces in the grate ash could be observed which was mainly due to the formation of K and Na-enriched silicates with melting temperatures of about 1050 °C. Regarding gaseous emissions, it can be stated that with CO and OGC emissions of on average 15.6 respectively 1.3 mg/Nm³ (dry flue gas, 13 vol% O_2) a very good gas phase burnout could be achieved. The average NOx emissions amounted to 247 mg/Nm³, but further NOx emission reduction potential of about 30% could be achieved by the optimised application of primary measures. As already expected from the evaluation of the wet chemical fuel analyses elevated HCl and SOx emissions had to be recognised amounting to on average 34 mg/Nm³ respectively 30 mg/Nm³. The total particulate matter emissions (TSP) (downstream the multi-cyclone) were clearly dominated by fine particulate emissions, which amounted to on average 91 mg/Nm³. Consequently, especially for larger-scale applications, the installation of a baghouse filter or an ESP for fine particulate emission control will be necessary. The analyses of the grate and cyclone fly ashes showed that the cycle of relevant plant nutrients (except N) could be almost closed by recycling the grate ashes or a mixture of the grate and the cyclone fly ashes to the maize fields.

The potential impact of the high potassium content of corn cobs was demonstrated in a series of tests performed within the AgroBioHeat project[23]. Two state-of-the-art combustion systems (boiler with moving grate boiler coupled with ESP for particulate control, boiler with innovative extreme air staging concept), suitable for residential applications and various assortments of agrobiomass fuels (olive stones, sunflower husk pellets, miscanthus, poplar, agropellets and maize cobs) were tested. The maize cobs tested exhibited a particularly high potassium content – more than 1% wt d.b. – which resulted in exceptionally high particulate emissions compared to the other agrobiomass fuels tested, as well as to increased flue gas temperatures and corresponding efficiency losses.

The peculiarities of corn cob combustion can be handled in medium-scale applications, through the use of appropriate technologies and know-how. The French boiler manufacturer Compte-R has developed several such corn cob-fired boilers since 2012. The key features of such systems include the use of water-cooled grates which keep temperatures below 850 °C, the appropriate design and construction of the combustion chamber and heat exchanger surfaces in order to lower flue gas temperature at the inlet of the tube sheets below 650 °C, and the use of appropriate flue gas cleaning systems to avoid the release of fine particles in the atmosphere[54]. Corn cob boilers of Compte-R have been installed at grain processing companies, but also for district heating plants.

THE ECO_2WACKEN DISTRICT HEATING NETWORK IN STRASBURG[55]

Since 2016, several key buildings of the Wacken district of Strasburg are supplied with heat from a boiler house featuring two Compte-R boilers, a 3.2 MW wood and a 2 MW corn cob one. The Eco_2Wacken network supplies 30 GWh/year of heat and uses 8,000 t of forest chips and 3,000 t of corn cob annually, with an average efficiency of 87%. The fuels are delivered by trucks (less than three schedules per day) and unloaded in two separate areas. The wood storage has a capacity of 300 m³, enough for four dates of operation, while the corn cob storage is of 180 m³ silo, guaranteeing two days of operation. Corn cobs are sourced for a nearby agricultural company; their combustion ash, rick in potassium, is recycled back to the farms for fertilization. Bag filters are used to keep the dust emissions to very low levels (below 10 mg/Nm³). Backup is provided by two 6 MW gas boilers, while a 95 m³ hot water tank provides possibilities for thermal storage. It is calculated that more than 7,000 t of CO_2 are saved annually through the operation of this district heating system.

[54] *https://www.bioenergie-promotion.fr/51630/compte-r-confirme-son-expertise-en-combustion-des-agrocombustibles-solides/*
[55] *https://www.bioenergie-promotion.fr/51570/bois-rafle-de-mais-pour-la-chaufferie-eco2wacken-de-strasbourg/*

MAIZE RESIDUES FOR POWER GENERATION

Maize residues can be used by CHP (Combined Heat and Power) and power plants, which operate on straw. In some cases, it can be used as additional biomass for co-firing with wood. The typical biomass-fired power plant uses direct combustion to burn biomass in a boiler to produce high-pressure steam, that drives a turbine and produces electricity. A CHP plant captures heat in addition and thus provides heat and power.

Many power plant projects for use of maize residues as fuel have been developed by the DP CleanTech. The company delivered the complete advanced straw-fired power plant Liaoyuan with a capacity of 30 MWe in Jilin Province of China in 2007. It runs on locally sourced fuels mainly from agricultural residues such as corn straw. The straw boiler is designed to handle hard fuels such as wood chips, which can be fed via the auxiliary silo contributing up to 35% of total fuel input. The plant consumes more than 160,000 tons of straw per year and reaches an availability of 7800 h/y. The straw-fired steam boiler operates with high steam parameters at 92 bar and 540 °C resulting in a net overall plant efficiency of more than 32% and boiler efficiency of over 93%. The straw is led to the boiler through a stoker and is then combusted on a water-cooled vibrating grate under carefully controlled conditions; the vibrating movements regulate the stages of combustion[56].

15 MWe Miajadas biomass power plant in Spain (Fig. 20, 21), which has been in service since 2010, consumes 110,000 metric tons of herbaceous (cereal straw, corn stover) and wood (pruning and forestry waste) biomass per year. It was developed as an R&D project together with companies and technology centers in Spain, Finland, and Denmark, with backing from the European Union's 7th Framework Program for support to research. The operator is Acciona Energía. The average annual production of the plant is 128 GWh, equivalent to the electricity demand of 40,000 homes. It is avoided 123,000 metric tons of CO_2 per year[57]. The power plant uses a steam boiler with vibrating grate and steam capacity of 71 t/h, Rankine cycle without regeneration and a dual-feed system for bales and wood chips[58].

The Danish company Babcock & Wilcox Vølund has supplied technology to a biomass-fired energy plant at the Bulleh Shah Packaging Limited paper factory in Pakistan[60]. The plant can utilize several different agricultural residues (wheat straw, corn stalks, rice stalks, cotton sticks, and others) from local farmers for production steam with a flow of 150 t/h. The nominal fuel capacity is 37.7 t/h. The boiler has B&W's Vølund water-cooled vibrating grate for efficient burning of the biomass. The ash produced from this boiler is being offered free of cost, which can be used as a fertilizer for crops at the time of cultivation, in the brick-making process and can be used as an alternative to sand while fixing tiles for flooring[61].

More information about straw heat and power plants can be found in the AgroBioHeat guide "Straw to Energy. Technologies, policy and innovation in Denmark. Second edition" (http://agrobioheat.eu/wp-content/uploads/2020/11/AgroBioHeat_D7.6_Straw_to_energy_EN.pdf).

[56] *https://www.dpcleantech.com/waste-and-biomass-clean-energy-technologies/combustion-technology/dp-wcv-grate/download/994/30/22*
[57] *https://www.acciona.com/projects/miajadas-biomass-plant/?_adin=01010174103*
[58] *http://ghesa.com/en/portfolio_page/miajadas/*
[59] *https://www.acciona-energia.com/es/areas-de-actividad/?_adin=0744759730*
[60] *https://www.babcock.com/-/media/documents/case-profiles/renewables/pch201-130-packages.ashx?la=ru-ru&hash=-F11E957E430907C7A937EE06E6AA6FAA852EB0A2*
[61] *https://www.packages.com.pk/wp-content/uploads/2020/09/Packages-Group-Sustainability-Report-2019.pdf*

FIGURE 20:
Miajadas 15 MW biomass plant

FIGURE 21:
Maize residues bales in the biomass storage facility of the Miajadas power plant[59]

MAIZE RESIDUES FOR BIOETHANOL

Corn plays a crucial role as feedstock for the ethanol production. According to reports of the European renewable ethanol association (ePURE), the Europe's renewable ethanol industry continues to grow. The installed production capacity (EU27 + UK) in 2020 was 9,992 million litres, while in 2019 it was 9,893 million litres. Members of ePURE used 6.67 million tonnes of corn for that purpose in 2020 which was 49.5% of the total volume of produced bioethanol (respectively, 6.56 million tonnes and 48.6% in 2019), that shows the importance of corn in first generation bioethanol production in the EU[62].

It is expected that maize residues could be an important feedstock for second-generation bioethanol, which is an advanced biofuel from lignocellulosic biomass. The contribution of advanced biofuels and biogas produced from the feedstock listed in Part A of Annex IX of RED II Directive as a share of final consumption of energy in the transport sector shall be at least 0.2 % in 2022, at least 1 % in 2025, and at least 3.5 % in 2030. It should be noted, that the advanced biofuels from these feedstocks may be considered to be twice their energy content in the contribution towards the minimum shares.

Bioethanol production from maize residues requires a pretreatment stage for destroying the lignocellulosic structure, which makes the access of enzymes to the cellulose chains easier or directs the use of their lignocellulosic fractions. A typical scheme of bioethanol production from lignocellulosic raw material is shown in Fig. 22. From one dry ton of corn stover, the potential ethanol yield is 428 litres. According to the data of the DuPont Nevada Site Cellulosic Ethanol Facility, 283.5 l of bioethanol can be produced from 1 t of harvested corn stover (Fig. 15). Also, maize from the field area could supply corn for the first-generation bioethanol production. Totally, 140.8 GJ can be obtained by the combustion of residues and biofuels from a hectare of maize[63].

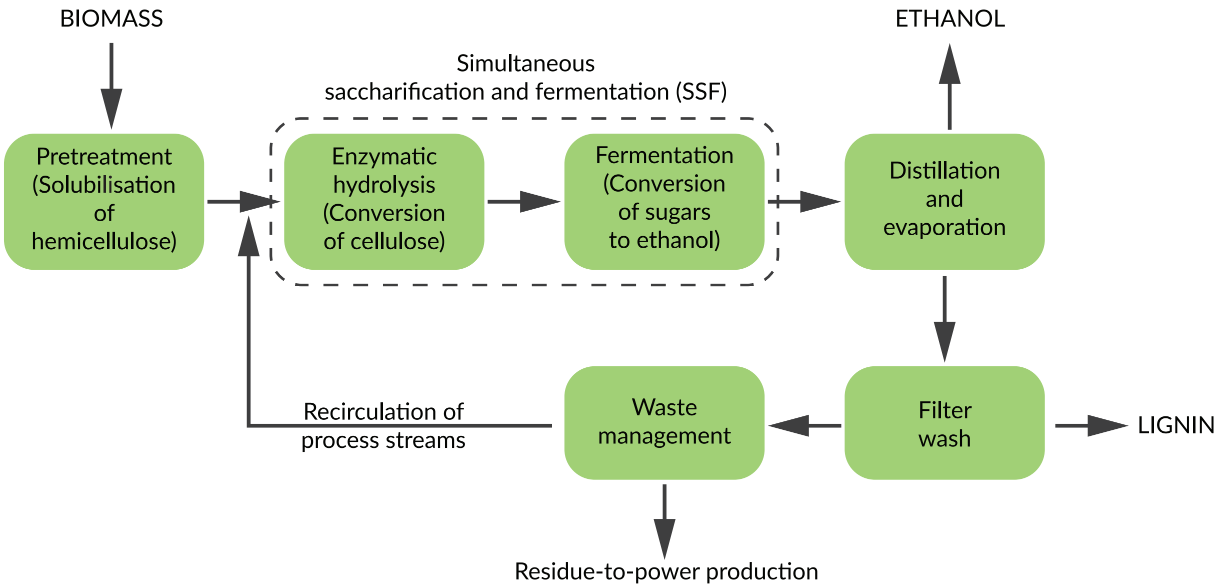


FIGURE 22:
Process of bioethanol production from lignocellulosic biomass[64].

[62] *https://www.epure.org/wp-content/uploads/2021/09/210823-DEF-PR-European-renewable-ethanol-Key-figures-2020-web.pdf*
[63] *Second-Generation Biofuel Markets: State of Play, Trade and Developing Country Perspectives. United Nations conference on trade and development – 69 p.*
[64] *M. N. A. M. Yusoff, N. W. M. Zulkifli, B. M. Masum and H. H. Masjuki Feasibility of bioethanol and biobutanol as transportation fuel in spark-ignition engine: a review. RSC Adv., 2015, 5, 100184–100211.*

Only a small number of facilities producing ethanol from cellulosic materials were operating successfully worldwide by the end of 2020[65]. The activities towards a market launch of lignocellulosic bioethanol have recently taken place mainly in the USA and Brazil[66]. Also, some second-generation bioethanol facilities were started in the EU and China, but only several of them are commercial plants that can produce bioethanol from maize residues.

In the USA, the total installed bioethanol production capacity was 66,000 mln l per year in 2020, which produced 52,239 mln l last year[67]. 4.1% of US bioethanol production capacities can use cellulosic biomass as feedstock, including, 0.4% operates only on cellulosic biomass. Some of them produce bioethanol from maize residues. The largest facilities currently are VERBIO North America Corp in Nevada with a production capacity of 113.5 mln l per year (30 mgy[68]) which was bought from DuPont, Project LIBERTY in Emmetsburg – 75.7 mln l per year (20 mgy), Seaboard Energy Kansas in Hugoton – 94.6 mln l per year (25 mgy).

In Brazil, bagasse is the main feedstock for cellulosic bioethanol. It is expected that 178 thousand tons of this biomass is used for the production of 32 mln l in 2020[69]. Plants have not reached full capacity due to operational/mechanical challenges. In China, Longlive Bio-technology Co. Ltd started up a cellulosic ethanol facility with a capacity of 60,000 tons per year in Shandong in 2012[70].

The forecast of USDA is 25 mln l of cellulosic ethanol production in the EU in 2020[71]. One of the world's largest cellulosic ethanol production facilities, the Beta Renewables plant officially opened at Crescentino (Italy) in 2013 but it has been shut down since 2017 due to a restructuring effort of the parent chemical company Mossi & Ghisolfi. The plant had an annual capacity of 40 kt of ethanol produced from wheat straw, rice straw, and giant reed (Arundo donax)[72]. The plant was acquired by Eni's chemical subsidiary Versalis in November 2018. The new operator planned to be up and running the facility in 2020.

COMETHA Project supported by the Seventh Framework Programme of the European Community from 2014 to 2018 involved the construction and operation of an integrated precommercial industrial facility for the production of 80,000 t/y of second-generation bioethanol starting from lignocellulosic biomass at Porto Marghera (Italy)[73]. The project addressed the development of the sustainable biomass supply chain based on 360,000 tonnes of lignocellulosic biomass per year derived from the Region of Veneto, such as dedicated perennial crops (Arundo donax) and agricultural residue (corn stover, the most suitable feedstock for bioethanol production in the considered geographical scenario).

In 2021, Europe's first commercial-scale cellulosic ethanol production plant will be completed by the Swiss company Clariant in Southwest Romania. One innovative solution developed by the company in that regard is the sunliquid® technology that creates value by converting agricultural residues, e.g., cereal straw, corn stover, rice straw, or sugarcane bagasse into cellulosic ethanol. The sunliquid® plant in Romania will produce 50,000 tons of cellulosic ethanol by converting 250,000 tons of locally sourced sustainable wheat straw. More than 400 green jobs will be permanently created by constructing the plant in a predominantly rural area – 100 of them in the plant itself and 300 in adjacent areas, e.g., in the feedstock supply chain. Besides, cellulosic ethanol projects are also underway in three other European countries – Slovakia, Poland, and Bulgaria – with Clariant's technology[74].

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[65] Renewables 2021 Global Status Report. https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf
[66] Technical options for retrofitting industries with bioenergy. BioFitHandbook https://www.biofit-h2020.eu/publications-reports/BioFitHandbook-2020-03-18.pdf
[67] Essential energy. 2021. Ethanol industry outlook. Renewable fuels association report. https://ethanolrfa.org/wp-content/uploads/2021/02/RFA_Outlook_2021_fin_low.pdf
[68] Million gallons per year
[69] Biofuels Annual. Brazil. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_08-03-2020
[70] https://www.etipbioenergy.eu/value-chains/conversion-technologies/advanced-technologies/sugar-to-alcohols
[71] Biofuels Annual. European Union. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_The%20Hague_European%20Union_06-29-2020
[72] Monica Padella, Adrian O'Connell, Matteo Prussi. What is still Limiting the Deployment of Cellulosic Ethanol? Analysis of the Current Status of the Sector Appl. Sci. 2019, 9, 4523; doi:10.3390/app9214523
[73] https://cordis.europa.eu/project/id/322406
[74] https://www.euractiv.com/section/alternative-renewable-fuels/opinion/making-european-sustainable-mobility-a-reality-with-cellulosic-ethanol/

MAIZE RESIDUES FOR BIOGAS

Maize silage is one of the most popular substrates used for feeding agricultural biogas plants. However, due to the growth of prices on maize silage, many biogas plant operators started to look for alternative substrates which can be easy to get, are inexpensive, and have good methane productivity[75]. Maize residues can be one of these substrates.

One advantage of using maize residues for anaerobic digestion is that the process is not affected by their potentially high moisture content after harvesting – which can be problematic for direct combustion processes. The fermented substrate from the biogas plant can be applied as a bio-fertilizer for recirculating nutrients to the farmland, along with part of the carbon.

Compared to maize silage, the anaerobic digestion of maize residues (straw) has a lower biogas potential (table 3). It also requires a higher retention time in comparison with maize silage but it is considered that such a difference could be accommodated by biogas plant operators.

TABLE 3:
Methane output from maize residues[76] and maize silage[77].

	DM, % wet weight	Biogas, l_N/kg VS	CH_4, l_N/kg VS	Degraded DM, %
1. Maize residues fractions				
• Stalks	25.5 ± 0.8	424.3	233.8	53.9
• Leaves	63.3 ± 0.8	442.9	244.5	57.0
• Husks	58.2 ± 0.6	544.4	307.0	70.4
• Cobs	43.5 ± 0.2	379.8	206.6	51.3
2. Maize silage	27.7	673	345	77.9

DM – dry matter; VS – volatile solids

[75] Mazurkiewicz, J.; Marczuk, A.; Pochwatka, P.; Kujawa, S. Maize Straw as a Valuable Energetic Material for Biogas Plant Feeding. Materials 2019, 12, 3848. https://doi.org/10.3390/ma12233848
[76] Simona Menardo, Gianfranco Airoldi, Vincenzo Cacciatore, Paolo Balsari Potential biogas and methane yield of maize stover fractions and evaluation of some possible stover harvest chains, Biosystems Engineering, Volume 129, 2015, 352-359. https://doi.org/10.1016/j.biosystemseng.2014.11.010.
[77] Bauer, A., Leonhartsberger, C., Bösch, P., Amon, B., Friedl, A., & Amon, T. (2009). Analysis of methane yields from energy crops and agricultural by-products and estimation of energy potential from sustainable crop rotation systems in EU-27. Clean Technologies and Environmental Policy, 12(2), 153–161. doi:10.1007/s10098-009-0236-1.

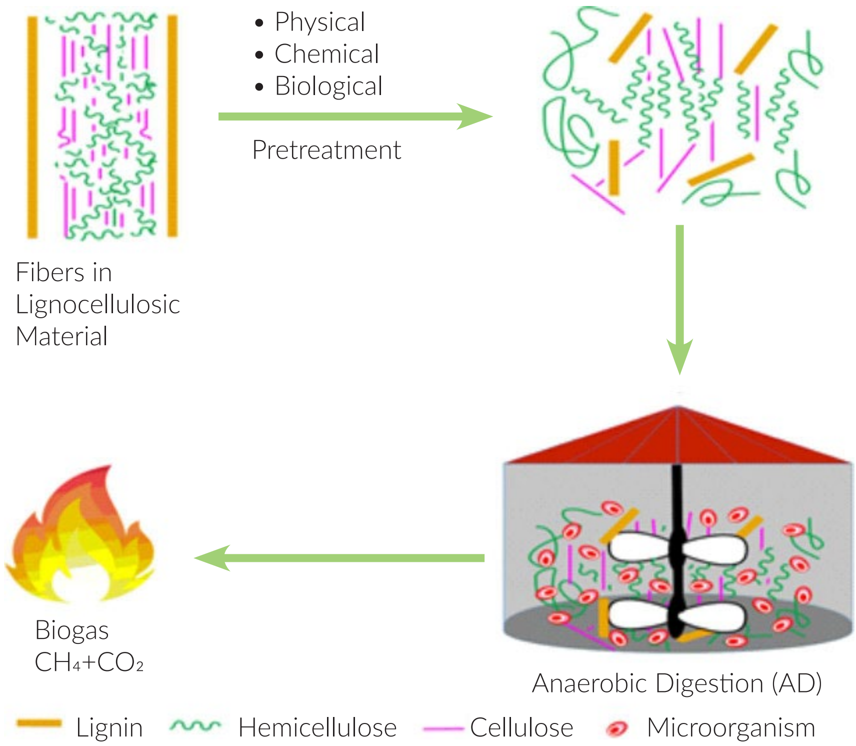

FIGURE 23:
Schematic diagram of the pre-treatment of lignocellulosic material for biogas production[81]

Due to the high content of lignocellulosic chemical compounds in maize residues (Table 2), they need to be pretreated for mechanical, physical, biological, or chemical destruction before the fermentation (Fig. 23). These processes improve the biogas yield and decrease the retention time of substrate in an anaerobic digester but require additional energy and costs. From an energetic point of view, only chemical pretreatment seemed to be sustainable[78]. The analysis of seven chemical pretreatments of corn straw shows, that straw pretreated with 3% H_2O_2 and 8% $Ca(OH)_2$ elicited the highest methane yields of 216.7 and 206.6 ml CH_4/g volatile solids (VS), which are 115.4% and 105.3% higher than that of the untreated straw, respectively[79]. These two processes are economically and effectively superior to the other compared pretreatments. Also, promising is biological pretreatment. Corn straw pretreated by composite microbes produced 131.6% more total methane than the untreated control[80].

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[78] *Croce, S., Wei, Q., D'Imporzano, G., Dong, R., & Adani, F. (2016). Anaerobic digestion of straw and corn stover: The effect of biological process optimization and pre-treatment on total bio-methane yield and energy performance. Biotechnology Advances, 34(8), 1289–1304. doi:10.1016/j.biotechadv.2016.09.004*
[79] *Song Z, GaiheYang, Liu X, Yan Z, Yuan Y, et al. (2014) Comparison of Seven Chemical Pretreatments of Corn Straw for Improving Methane Yield by Anaerobic Digestion. PLoS ONE 9(4): e93801. doi:10.1371/journal.pone.0093801*
[80] *Panpan Li, Chao He, Gang Li, Pan Ding, Mingming Lan, Zan Gao & Youzhou Jiao (2020) Biological pretreatment of corn straw for enhancing degradation efficiency and biogas production, Bioengineered, 11:1, 251-260, DOI: 10.1080/21655979.2020.1733733*
[81] *Amin, F.R., Khalid, H., Zhang, H. et al. Pretreatment methods of lignocellulosic biomass for anaerobic digestion. AMB Expr 7, 72 (2017). https://doi.org/10.1186/s13568-017-0375-4*

In 2013, there was commissioned a pilot plant for mono-digestion of corn straw with an electrical capacity of 50 kW in Renqiu in China[82]. The biogas plant consists of 40 m³ continuously feeding hydrolysis for pretreatment stage and 2 digesters 476 m³.

In December 2019, AB Energy SPA from Spain launched biomethane production with a flow rate of 606 Nm³/h from agricultural feedstocks, including corn stalks, in Milan. The biomethane fed into the Italian gas network[83].

The industrial biogas technologies for using maize residues and other crop residues as feedstock are developing. Such a new project of EnviTec Biogas (Germany) will be constructed near Qin Xian City in Shaanxi Province of China. Once completed, the biogas plant's four digesters will generate about 37,000 Nm³ of biogas daily from farm residue such as maize stalks[84]. The three-stage membrane gas upgrading procedure, patented by Evonik, enables biogas to be refined to biomethane with low levels of methane loss[85].

In Khmelnitsky region of Ukraine, a biogas plant is built by the Teofipol Energy Company with an electrical capacity of 10.5 MW, which will use crop residues, including a large volume of maize residues.

Verbio (Germany) announced the installation of an anaerobic digester at the former DuPont cellulosic ethanol plant in Nevada in the USA, which will use 100,000 tonnes of corn stover annually to produce biomethane with the energy equivalent of 80 million litres of petrol[86].

[82] *Bionova Biogas GmbH. Map with references Semi-aerobic Hydrolysis Facilities in Germany and around the world https://bionova-biogas.de/en/pdf/2014_References_Bionova.pdf*
[83] *Biogas success stories 2020. European Biogas Association. https://www.europeanbiogas.eu/wp-content/uploads/2020/11/EBA_catalogue2020_WEB-1.pdf*
[84] *Biogas barometer 2020. EurObserv'ER https://www.eurobserv-er.org/pdf/biogas-barometer-2020/*
[85] *https://www.bioenergy-news.com/news/construction-underway-on-two-envitec-biogas-projects-in-china/*
[86] *Renewables 2021 Global Status Report. https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf*

SUSTAINABILITY ASPECTS OF MAIZE RESIDUES UTILIZATION

SUSTAINABLE REMOVAL OF MAIZE RESIDUES

Indiscriminate harvesting of crop residues can induce deleterious effects on soil functioning, plant growth, and other ecosystem services[87]. The reduction in the input of organic residues into the soil implies a direct reduction in C stocks, which negatively affects the soil biota. But, the impacts of crop residue management on soil GHG emission are still not fully understood and demand more field studies. In general, the harvesting of residues reduces emissions of CO_2 and N_2O produced by decay and has no effects on CH_4 emission. However, the gradual depletion of C and N stocks in the soil, associated with the replacement of N via mineral fertilizers, could induce a negative C balance and higher N_2O emissions in areas where the residues are harvested. The plant response to crop residue management is site-specific, and for sustainable bioenergy production, there can be applied different best management practices (e.g. conservation tillage, crop rotation and cover crops, nutrient management, and/or organic residues).

In the same way, the maize residues harvesting strategy depends on the local conditions. A conceptual illustration of how economic drivers must be balanced against limiting factors based on soil protection and provision of ecosystem services is shown in Fig. 24.

To help farmers to make a rational decision, the specific guidelines for residue harvest were developed by USDA-Natural Resource Conservation Service in an effort to prevent soil degradation resulting from over-harvest of maize residues[89]. According to the document, sustainable crop residue removal rates for biofuel production will vary by factors such as management, yield, and soil type. Tools like RUSLE, WEQ, and the Soil Conditioning Index are likely to be the most practical ways to predict safe removal rates. Re-

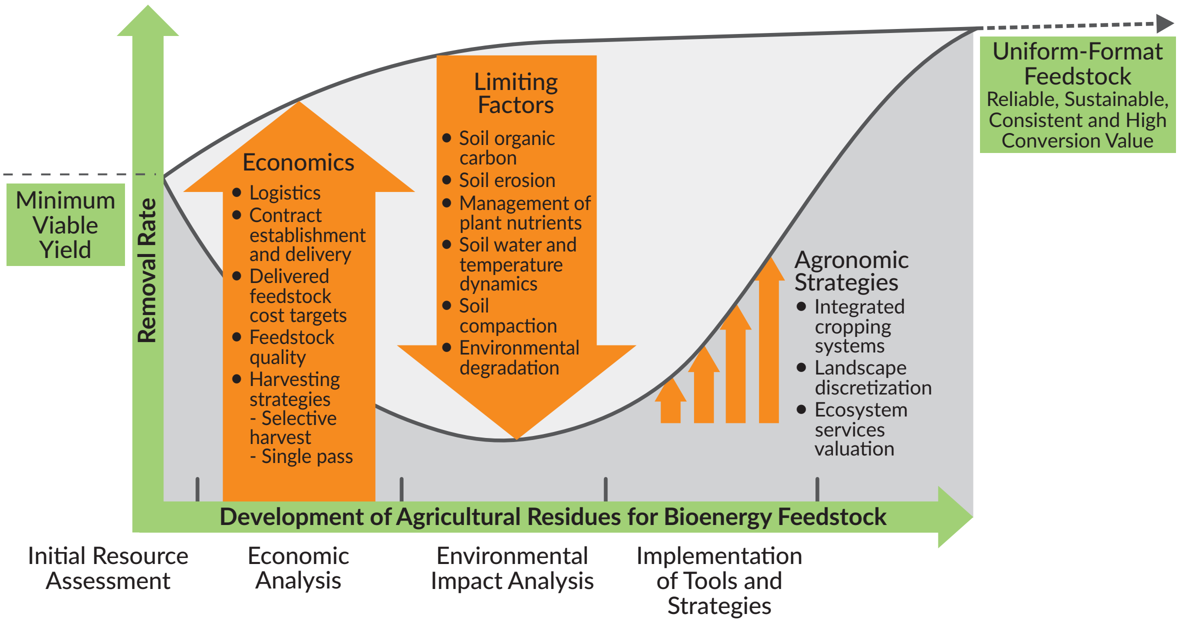

FIGURE 24:
Dependence of removal rate of maize residue on economics, limiting factors, and agronomic strategies[88]. The bars to the right illustrate various soil and crop management practices that can be implemented to help ensure sustainable feedstock supplies are developed and available.

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[88] Cherubin Maurício et al. (2018). Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. Scientia Agricola, v.75, n.3, 55-272. 75. doi:10.1590/1678-992X-2016-0459
[89] https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=2442&context=usdaarsfacpub

moval rates are not the same as percent soil cover: appropriate conversion is necessary and will vary by crop and region. While areas with low slopes and high yields may support residue harvest, in many areas the residue amounts required for maintaining soil quality will be higher than current soil cover practices. Some companies provide sustainable harvest residue removal, for example, Pacific Ag[90] determines with each grower, field-by-field, the right amount of residue to harvest to ensure moisture and soil protection needs are met while optimizing the effectiveness of tilling, inputs and emergence.

GHG EMISSIONS FROM MAIZE RESIDUES LOGISTICS

Maize residues should meet the RED II greenhouse gas emission reduction and non-GHG sustainability criteria (e.g. soil quality and soil carbon, biodiversity, and carbon stocks) when used at large plants (≥20 MW). The sustainable assessment of the CHP supply chain of corn stover in Romania is presented in the report of the Smart CHP EU research project[91]. This supply chain is assessed on total emission values for biomass supply, the fast pyrolysis bio-oil (FPBO) production process and transportation of FPBO from virtual plant location to end-user. Not only pyrolysis oil is produced within the process, but also steam and electricity as co-products. Results show that the emission reduction values of the Smart CHP supply chain of corn stover are 95% for electricity and 96% for heat in the case of assuming minimal FPBO transportation distance of 50 km and 94% and 96% respectively for 150 km. The total GHG emissions of corn stover supply are 2.0 $gCO_{2\text{-eq}}$/MJ biomass, including the emission of corn stover collection 0.88 $gCO_{2\text{-eq}}$/MJ biomass.

In the USA, corn stover-derived electricity and fuels, compared to their conventional counterparts, reduce GHG emissions by 21–92%. The environmental benefit is greatest for combined heat and power in the reference scenario of displacing the US average grid and natural gas (1.4 $tCO_{2\text{-eq}}$ per t corn stover)[92], which is shown in Fig. 25. The case study in Jilin Province of China[93] indicates that the utilization of pellets from corn straw can eliminate 90.46% of the life cycle GHG emissions by replacing coal burning. However, there are different fears associated with maize residues similar to other types of crop residues harvesting from the fields.

Thus, energy production from maize residues emits relatively small GHG emissions, which can be calculated by using approved emission reduction calculation methodology for a specific value chain. In the case of solid biomass only installations producing electricity, heating and cooling or fuels with a total rated thermal input equal to or exceeding 20 MW shall fulfil the sustainability and greenhouse gas emissions saving criteria according to the European Renewable Energy Directive (REDII).

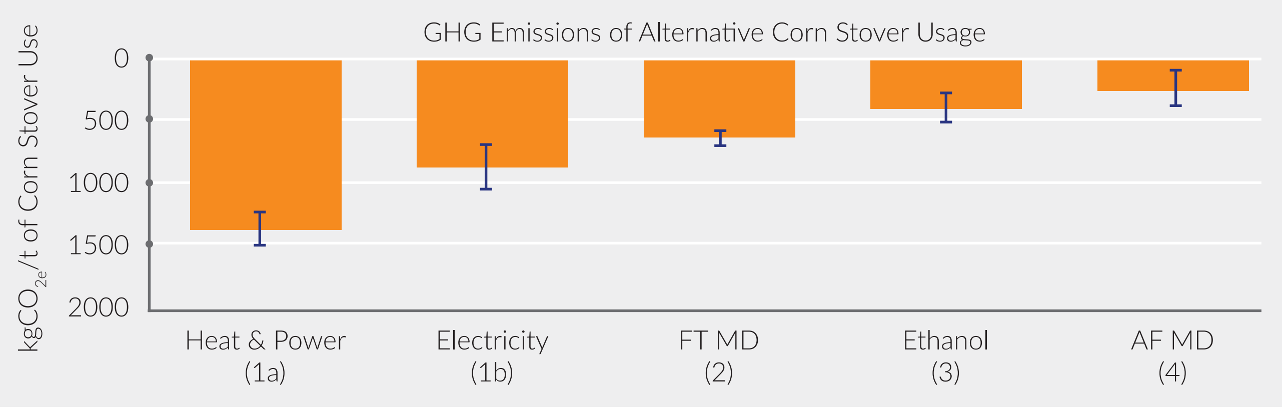

FIGURE 25:
Greenhouse gas emissions reduction from alternative corn stover use compared to the US grid average where: FT is Fischer–Tropsch; MD is middle distillate; AF is advanced fermentation[92].

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[89] Susan S. Andrews. White paper. Crop Residue Removal for Biomass Energy Production: Effects on Soils and Recommendations // USDA-Natural Resource Conservation Service – February 22, 2006.
[90] https://pacificag.com/harvesting/
[91] D5.1 SUSTAINABILITY ASSESSMENT_ BTG_ JUNE 2020 https://www.smartchp.eu/?jet_download=1799
[92] Trivedi, P., Malina, R., & Barrett, S. R. H. (2015). Environmental and economic tradeoffs of using corn stover for liquid fuels and power production. Energy & Environmental Science, 8(5), 1428–1437. doi:10.1039/c5ee00153f
[93] Shizhong Song, Pei Liu, Jing Xu, Chinhao Chong, Xianzheng Huang, Linwei Ma, Zheng Li, Weidou Ni, Life cycle assessment and economic evaluation of pellet fuel from corn straw in China: A case study in Jilin Province, Energy (2017), doi: 10.1016/j.energy.2017.04.068

ANNEX I: MAIN TYPES OF MACHINERY FOR HARVESTING, LOGISTICS OF MAIZE RESIDUES, AND PROCESSING THEM INTO PELLETS/BRIQUETTES

More information from machinery builders and dealers can be found in the online table at the link below:
https://docs.google.com/spreadsheets/d/1o-u1S0B5IXwjQW72b7C_G5kNAwmxE6-I6VcyEd6myog/edit#gid=0

Logo	Contact	Description	Shredding/ windrow-ing	Baling	Collecting/ loading/	Transport	Pelletizing/ Briquetting
BIOG	BioG GmbH Weilbolden 18, 4972 Utzenaich Austria +43 (0) 7751/50149–0 office@biog.at https://biog.at	The BioChipper developed by BioG, a mulch concept with swath consolidation, enables the harvesting of field residues such as corn straw, rapeseed straw, grain straw, catch crops and landscaping materials. The operations of suctioning, chopping, and swathing are carried out in a single step.	●				
HINIKER	HINIKER COMPANY 58766 240th Street Mankato, MN 56002 USA (507)-625-6621 (800)-433-5620 https://www.hiniker.com	A Hiniker 5600 Series Flail Windrower can substantially cut your field time by shredding and windrowing stalks in one pass.	●				
LOFTNESS	LOFTNESS COMPANY 650 South Main Street PO Box 337 Hector, MN 55342 USA 320-848-6266 info@loftness.com https://www.loftness.com	The Windrowing Shredder is the latest example of Loftness turning a challenge into an opportunity. Unpredictable markets and the demand for biomass are turning crop residue into a profit center.	●				
CLAAS	CLAAS https://www.claas-group.com/	Claas is the global producer of self-propelled forage and combines harvesters. CLAAS is also a top performer in worldwide agricultural engineering with tractors, agricultural balers, and green harvesting machinery.		●	●		

Logo	Contact	Description	Shredding/ windrow-ing	Baling	Collecting/ loading/	Transport	Pelletizing/ Briquetting
KRONE	**Maschinenfabrik Bernard KRONE GmbH & Co. KG** Zentrale: Heinrich-Krone-Straße 10 D-48480 Spelle Tel.: +49 (0)5977/935-0 Fax: +49 (0)5977-935-339 Info.ldm@krone.de https://landmaschinen.krone.de/	As a forage specialist, KRONE manufactures disc mowers, tedders, rakes, forage wagons, and silage trailers, round and square balers as well as the high-capacity and self-propelled BiG M mower conditioners and our BiG X forage harvesters.		●	●	●	
KUHN	**Kuhn Group** KUHN SAS 4 Impasse des Fabriques BP 50060 F-67706 Saverne CEDEX +33(0)3 88 01 81 00 Fax: +33(0)3 88 01 81 01 https://www.kuhn.com/	Kuhn Group is the global producer of hay and forage harvesting machinery. Kuhn produces shredders, rakes, and balers.	●	●			
AGCO Your Agriculture Company	**AGCO Corporation** https://www.agcocorp.com	Through well-known brands including Challenger®, Fendt®, GSI®, Massey Ferguson®, and Valtra®, AGCO Corporation delivers agricultural solutions to farmers worldwide through a full line of tractors, combine harvesters, hay and forage equipment, seeding and tillage implements, grain storage, and protein production systems AGCO's hay and forage solutions range from mowers and balers to forage blowers and storage boxes, all with innovations in size, capacity, and efficiency.		●	●		
CNH INDUSTRIAL	**CNH Industrial** https://www.cnhindustrial.com/	CNH Industrial produces and sells agricultural and construction equipment, trucks, commercial vehicles. Brands of the company, which present machinery for agricultural residues harvesting and logistics, are New Holland, Case, Iveco.	●	●	●	●	
JOHN DEERE	**John Deer** https://www.deere.com	Since founding in 1837, John Deere has delivered products and services to support those linked to the land. John Deere produces a wide range of machinery for biomass harvesting, including balers and loaders.	●	●	●		

Logo	Contact	Description	Shredding/ windrow-ing	Baling	Collecting loading/	Transport	Pelletizing/ Briquetting
arcusin	**Arcusin S.A.** Polígono Industrial Pla d'Urgell - Av. Merlet, 8 - 25245 VILA-SANA Lleida (Spain) T 973 71 28 55 - 696 98 29 10 arcusin@arcusin.com https://www.arcusin.com	The company produces machinery for the bale-handling sector. Automatic bale loader AutoStack FSX and XP54. Bales accumulator ForStack 8.12			●		
ЗАВОД КОБЗАРЕНКА	**ZAVOD KOBZARENKO LTD** Ukraine, 42500, Sumy region., Lypova Dolyna, Rusaniwska street, 17 +38 (044) 451-68-77, +38 (095) 277-63-98 www.kobzarenko.com.ua	Production of equipment for collecting and transporting bales. - trailer for square bales PT-16 KVADRO; - self-loading trailers for round bales; - platform trailers.			●	●	
PROAG	**ProAG** 2131 Airport Drive Saskatoon, SK Canada S7L 7E1 306-933-8585 https://www.proagdesigns.com/	ProAG bale carriers are designed for either round or large square bales for their picking and stacking.			●		
URSUS	**URSUS S.A.** **DOBRE MIASTO - HQ** ul. Fabryczna 21, 11-040 Dobre Miasto Poland +48 22 506 56 00 dobremiasto@ursus.com https://www.ursus.com/	URSUS is undoubtedly the oldest Polish trademark of vehicles, machines, and devices manufactured for the needs of agriculture, among which there are balers (including those intended for hay silage) and platforms for bales transportation.		●		●	
KAHL	**AMANDUS KAHL GmbH & Co. KG** Dieselstrasse 5–9 21465 Reinbek Hamburg, Germany +49 (0) 40 72 77 10 info@akahl.de https://akahl.de	Pelleting of renewable raw materials for energy recovery has been a topic for KAHL. Straw and dried forage pelleting plants have formed part of KAHL delivery program.					●

Logo	Contact	Description	Shredding/ windrow-ing	Baling	Collecting loading/	Transport	Pelletizing/ Briquetting
CPM EUROPE Your Partner in Productivity	**CPM Europe B.V.** Rijder 2, 1507 DN Zaandam The Netherlands +31 75 65 12 611 info@cpmeurope.nl https://www.cpmeurope.nl/	CPM Europe produces high-end equipment for pelleting and grinding a large variety of wood and agricultural products.					●
ANDRITZ	**ANDRITZ Feed and Biofuel A/S** Esbjerg, Denmark Phone: +45 72 160 300 andritz-fb.dk@andritz.com https://www.andritz.com	ANDRITZ can design, manufacture, supply, and optimize the machinery for producing high-quality biomass pellets. Our solutions are always backed by technical consulting, engineering, installation, and aftermarket service by our global service centres.					●
ICK GROUP	**ICK GROUP** office 222, 89 A, Prospect Peremogy, Kyiv, 03115, Ukraine tel.: +38 (067) 215 10 32 fax: +38 (044) 451 02 30 e-mail: info@ick.ua https://ick.ua/	ICK Group manufactures equipment under GRANTECH own trademark. Many years of experience in the implementation of energy-saving technologies and technologies for pelletizing of different materials.					●
C.F. Nielsen A-S	**C.F. Nielsen A/S** Solbjergvej 19 DK-9574 Baelum tel: +45 9833 7400 https://cfnielsen.com/	C. F. Nielsen is the leading global brand in designing and producing mechanical briquetting solutions for biomass and waste.					●
	PE "Briquetting Technologies" 13313, Ukraine, Zhytomyr region, c. Berdychiv, Semenivska str., 116 +38 (067) 410 21 02 bricteh@gmail.com https://briq-tech.com/	The complex of equipment for the production of fuel briquettes and pellets.					●

ANNEX II: ENERGY SYSTEMS TO PRODUCE HEAT FROM MAIZE RESIDUES

More information from boiler producers can be found in the online table at the link below:
https://docs.google.com/spreadsheets/d/1hb1IEKkxIR_0StT5L0ibOfZzggeZ-BjeARq33iwjiaE/edit#gid=0

Logo	Contact	Description	Small boilers (100-500 kW)	Middle boilers (500 kW – 1 MW)	Large boilers (above 1 MW)	Steam boilers
	Group COMPTE.R https://www.compte-r.com/en/	For over 130 years, COMPTE.R has been innovating and inventing new biomass heating solutions for the development of renewable energies, until becoming a specialist in biomass energy.			●	●
	DP CleanTech https://www.dp-cleantech.com/	DP's biomass solutions portfolio consists of proven, patented and leading technologies for combustion, gasification and biogas conversion of biomass to clean energy.			●	●
	Babcock & Wilcox Vølund https://www.babcock.com/	B&W delivers environmentally conscious, technology-driven solutions and services to energy and industrial customers worldwide – safely, ethically and as promised.			●	●
	TTS eko s.r.o. https://www.ttsboilers.cz/	Within the ecological program the company TTS mainly deal with the development, production, assembly and servicing of industrial boilers and boiler houses for biomass combustion.			●	
	Volyn-Kalvis LLC https://www.volyn-kalvis.com.ua/en/	Volyn-Kalvis LLC produces water heating automated solid fuel boilers with moving grate for different types of biomass: sawdust, wood chips, grain waste, sunflower and corn stalks, as well as pellets from wood, sunflower, peat and other plant materials.	●	●	●	
	Kriger boiler plant https://kriger.com.ua/	Kriger boiler plant is a company with a complete cycle of turnkey construction for a business connected with the thermal energy production.		●	●	●

AGROBIOHEAT CONSORTIUM

Logo	Description
CERTH CENTRE FOR RESEARCH & TECHNOLOGY HELLAS	Centre for Research and Technology Hellas (CERTH) is one of the leading research centres in Greece. Among its areas of expertise, activities in renewable energy sources, solid biofuels production and utilization, energy saving and environmental protection are included. www.certh.gr
aveBiom Asociación Española de la Biomasa	AVEBIOM is the Spanish Bioenergy Association which represents all the companies of the whole supply chain of the bioenergy in Spain. www.avebiom.org
BIOS BIOENERGIESYSTEME GmbH	BIOS is an Austrian R&D and engineering company with more than 20 years of experience in the field of energetic biomass utilisation. www.bios-bioenergy.at
Bioenergy EUROPE	Bioenergy Europe (formerly known as AEBIOM) is the voice of European bioenergy. It aims to develop a sustainable bioenergy market based on fair business conditions. www.bioenergyeurope.org
Food & Bio Cluster Denmark	Food & Bio Cluster Denmark is the national Danish cluster for food and bioresources. We promote increased cooperation between research and business and offer our members one-stop-shop access to networks, funding, business development, projects, facilities and offer various consultancy services. www.foodbiocluster.dk
circe RESEARCH CENTRE FOR ENERGY RESOURCES	Technology Centre funded in Spain in 1993, seeking to provide innovative solutions in the field of energy for a sustainable devel-opment. www.fcirce.es
INASO-PASEGES	INASO-PASEGES is a civil non profit organisation, established in 2005 in Athens by the Panhellenic Confederation of Unions of Ag-ricultural Cooperatives (PASEGES). www.neapaseges.gr
ZEZ Zelena Energetska Zadruga	The Green Energy Cooperative (ZEZ) was established in 2013 as part of the project “Development of Energy Cooperatives in Croa-tia” implemented by the United Nations Development Program (UNDP) in Croatia. www.zez.coop
GREEN ENERGY Romanian Innovative Biomass CLUSTER	The Cluster’s main purpose is to develop the bioenergy sector in Romania and raising the interest towards the production and utilization of the biomass. www.greencluster.ro
UABIO	UABIO was established in 2013 as a public organisation. The purpose of the Association’s activity is to create a common platform for cooperation on the bioenergy market of Ukraine. www.uabio.org

Logo	Description
	AILE is working on renewable energies and energy savings in agri-cultural and rural areas of Western France. www.aile.asso.fr
	White Research is a social research and consulting enterprise spe-cialising in consumer behaviour, market analysis and innovation management based in Brussels. www.white-research.eu
	Agronergy is a French ESP (Energy Service Provider) dedicated to Renewable Heating. www.agronergy.fr


AVERO

PUBLICATION

This publication from Bioenergy Association of Ukraine (UABIO) and Centre for Research and Technology Hellas (CERTH) covers issues related to the current state of the maize production, features of its cultivation and the possibilities of using maize residues for energy. The guide provides a review of technologies for maize residues harvesting and their use for heat, energy, biogas and bioethanol production. It also includes lists of companies, which offer machinery for harvesting, logistics of maize residues, processing them into pellets/briquettes and energy systems to produce heat from maize residues. The guide has been created in the project AgroBioHeat, which is co-funded by the Horizon 2020 programme of the European Union. AgroBioHeat aims to promote economically and environmentally sustainable agro-biomass heating solutions in Europe.

AgroBioHeat

UABIO

CERTH
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RESEARCH & TECHNOLOGY
HELLAS

This project has received funding from the
European Union's Horizon 2020 research and innovation
programme under Grant Agreement No 818369