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ANALYSIS OF PELLETS AND BRIQUETTES PRODUCTION FROM CORN RESIDUES

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1 AVAILABILITY OF RAW MATERIALS FROM CORN RESIDUES

Summary

Position Paper No. 23 of the Bioenergy Association of Ukraine presents the techno-economic analysis of corn residues harvesting and their processing into pellets and briquettes. The topicality of the subject is explained by the fact that the yield of corn has been increasing in recent years in Ukraine, which creates the possibility to implement harvesting technologies for the residues of this crop approved in the US and EU and better fuel characteristics of this agricultural biomass compared to other types of the agribiomass, for example, cereal straw. Processing of corn residues into solid biofuels, including pellets and briquettes, is economically feasible. There is domestic and import equipment for such activity in the market.

1.1. STATE OF THE ART OF CORN PRODUCTION IN THE WORLD AND IN UKRAINE

Corn is the most high-yield crop, all the parts of which (Fig. 1.1) are widely used in different industries for many purposes (Fig. 1.2), in particular:

- for food production;
- as high-energy fodder in animal husbandry and poultry farming;
- as raw material for the production of first and second-generation biofuels;
- as raw material for the production of biogas;
- as raw material for the production of solid biofuels;
- as fertilizers;
- as feedstock in pharmaceutical, chemical, and other branches of industry.

a) corn grain *b) ears with wrap* *c) corn stalks* *d) cobs*

Fig. 1.1. Main parts of corn

Corn is a crop of high agro-technological value as it cleans soil of weeds and is an excellent precursor in the crop rotation. Judging by the absorption of carbon dioxide and release of oxygen, corn is one of the best crops and is even more effective than forest of the same area[1]. Valuable properties of

[1] *D. Shpaara. Corn. Growing, harvesting, conservation and use // K: LTD «Alpha-stevia», 2009 – 396 p.*

corn cause its constantly high demand in the world market. More information about the properties and features of the corn cultivation is provided in ***UABIO's Position Paper №16*** "Opportunities for harvesting by-products of grain corn for energy production in Ukraine".

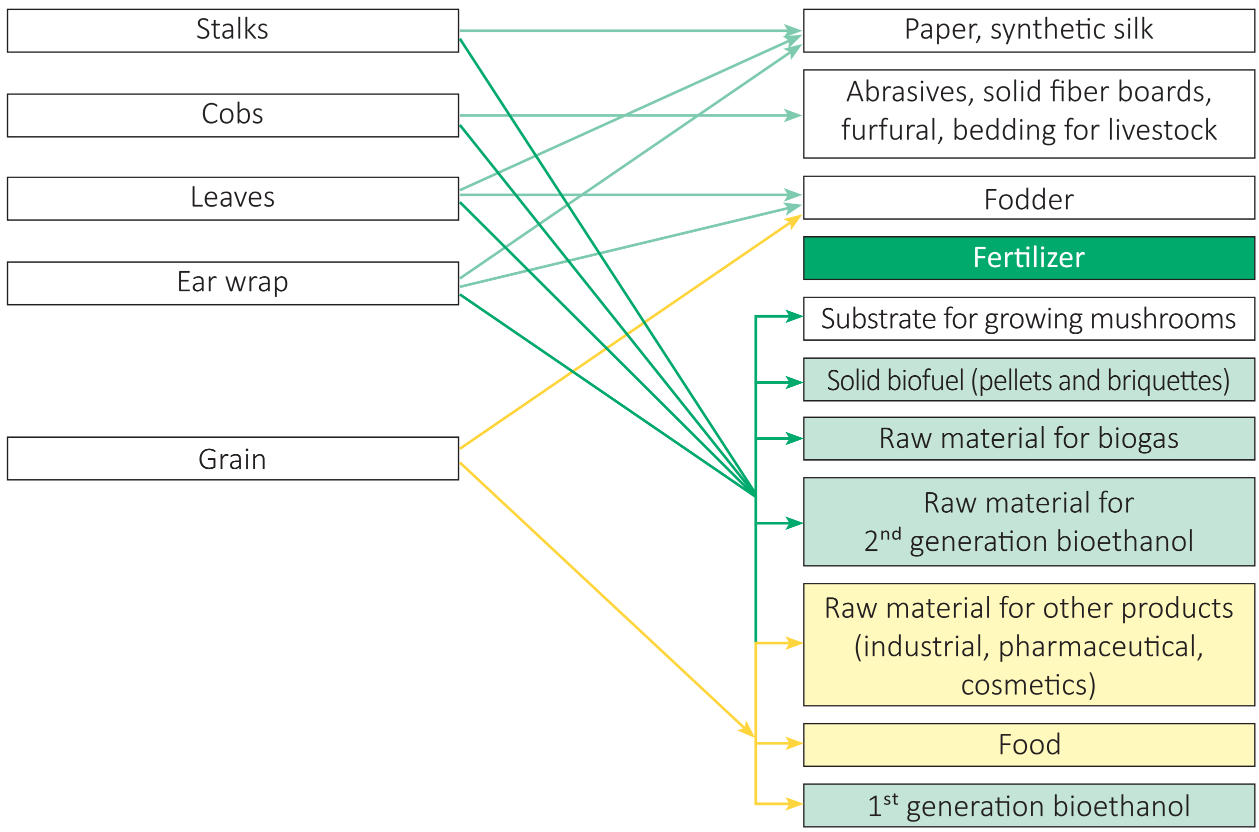

Fig. 1.2. Lines of using corn grain and corn residues

The USA is the world leader in corn production and yield. According to some preliminary data, the production of corn in the USA in 2018/2019 marketing year (MY) was 364.3 Mt (32.5% of the global production), and the average yield was 11.1 t/ha (Table 1.1). In other countries, the production of corn in 2018/2019 MY was the following: China – about 257.3 Mt, Brazil – 101 Mt, the EU – 64.2 Mt, Argentina – 51 Mt, and Ukraine – 24 Mt (the 6th place in the world). At that, the USDA forecast[2] for Ukraine for 2019/2020 MY is 35.5 Mt, which is lower than the historical record of 2018.

The increase in corn yield is associated with the development of agricultural science and the use of biotechnology for the creation of hybrids. Since 2000, it has provided 2% of the annual increase in the corn yield in the USA[3]. In comparative tests, American farmers manage to achieve corn yields at the level of over 250 m.c./ha. In 2019, the USA National Corn Growers Association announced the world record in Virginia – about 386 m.c./ha (616.2 bushels/acre) of grain corn[4].

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[2] *World Agricultural Production, USDA Reports https://apps.fas.usda.gov/psdonline/circulars/production.pdf*
[3] *http://agriculture.by/articles/rastenievodstvo/urozhajnost-kukuruzy-budet-rasti.-pochemu*
[4] *https://www.ocj.com/2019/12/2019-national-corn-yield-contest-hits-new-yield-record/*

Table 1.1. Main producers of corn in the world (by MY)[2]

№	Country / region	Area, million ha						Yield, t/ha						Production, million t					
		2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019	2019/2020
1	**USA**	**33.6**	**32.7**	**35.1**	**33.5**	**32.9**	**33.0**	**10.7**	**10.6**	**11.0**	**11.1**	**11.1**	**10.6**	**361.1**	**345.5**	**384.8**	**371.1**	**364.3**	**347.8**
2	China	37.07	38.1	44.2	42.4	42.1	41.3	5.8	5.9	6.0	6.1	6.1	6.3	215.6	224.6	263.6	259.1	257.3	260.8
3	Brazil	15.8	16.0	17.6	16.6	17.5	18.1	5.4	4.2	5.6	4.9	5.8	5.6	85.0	67.0	98.5	82.0	101.0	101.0
4	EU	9.5	9.3	8.6	8.3	8.3	8.7	8.0	6.4	7.2	7.5	7.8	7.5	75.7	58.8	61.9	62.0	64.2	65.0
5	Argentina	3.2	3.7	4.9	5.2	6.0	6.1	8.3	8.0	8.4	6.2	8.4	8.2	29.8	29.5	41.0	32.0	51.0	50.0
6	**Ukraine**	**4.6**	**4.1**	**4.2**	**4.4**	**4.6**	**4.9**	**6.2**	**5.7**	**6.6**	**5.4**	**7.8**	**7.2**	**28.5**	**23.3**	**28.0**	**24.1**	**35.8**	**35.5**
7	India	9.3	8.7	9.6	9.4	9.2	9.5	2.6	2.6	2.3	3.1	3.0	3.1	24.2	22.6	25.9	28.8	27.2	29.0
8	Mexico	7.33	7.2	7.5	7.3	7.2	6.8	3.5	3.6	3.7	3.8	3.8	3.7	25.5	26.0	27.6	27.6	27.6	25.0
	World	**178.6**	**180.6**	**194.5**	**192.1**	**191.7**	**192.2**	**5.7**	**5.4**	**5.8**	**5.6**	**5.9**	**5.8**	**1023**	**972**	**1123**	**1080**	**1122**	**1111**

Notes: 2018/2019 MY – preliminary data, 2019/2020 MY – forecast (January 2020)

Corn has been one of the main agricultural crops in Ukraine during at least the last decade (Fig. 1.3). Despite some fluctuations, the general trend has been the rise in grain corn yield (Fig. 1.4). According to data of 2018, the sown area under corn was 4564 th. ha (which was approx 31% of the planted area under all grain and leguminous crops), the production was 35.8 Mt, and the yield was 78.4 m.c./ha. In 2019, the sown area under corn increased to 4.9 mln. ha.

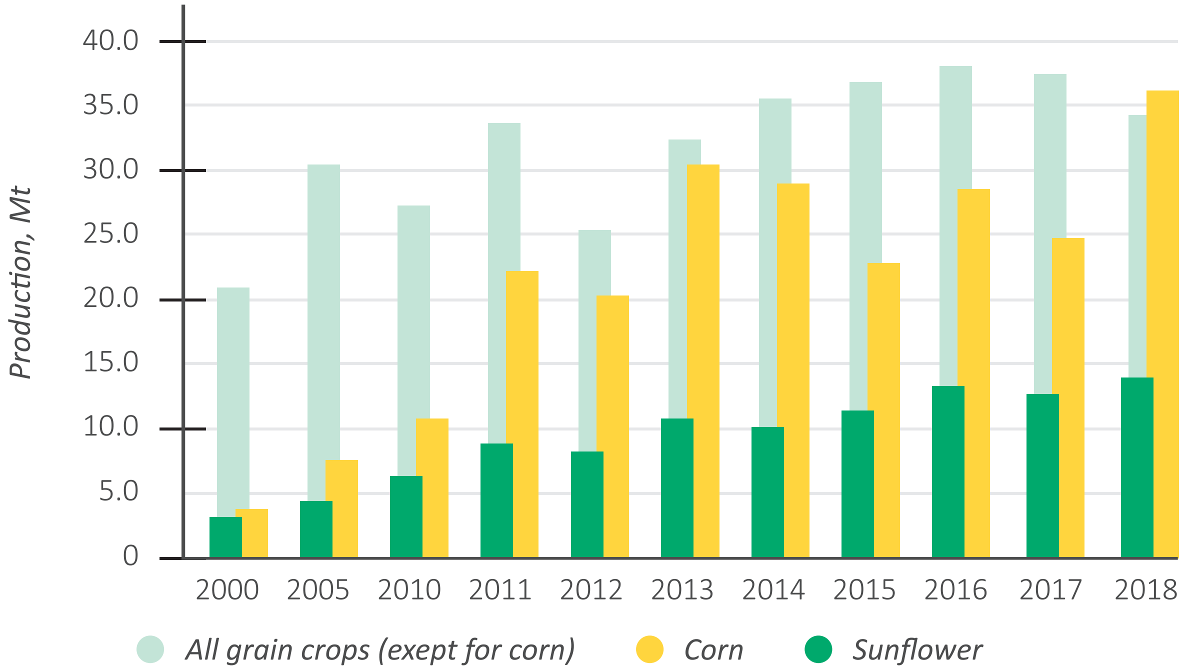


Fig. 1.3. Production of grain crops and sunflower in Ukraine[5]

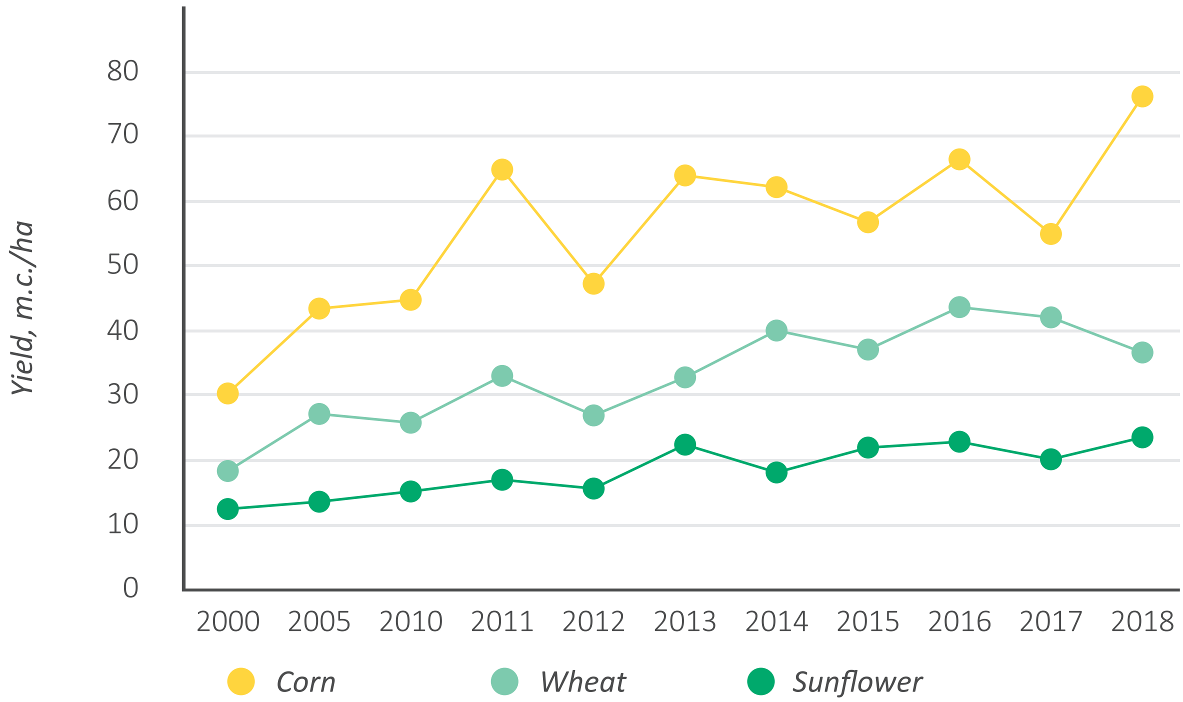


Fig. 1.4. Yield of wheat, corn, and sunflower in Ukraine[5]

[5] *Crop production in Ukraine 2018. Statistical Yearbook by the State Statistics Service of Ukraine, 2019 http://www.ukrstat.gov.ua/*

Data on the gross harvest (production) of grain corn, its harvested area, and yield in Ukraine's regions are given in Table 1.2. It can be seen that Poltava oblast is the leader among Ukraine's regions in corn production (nearly 4.9 Mt in 2018) followed by Chernihiv oblast (3.8 Mt in 2018) and Vinnytsia oblast (3.8 Mt in 2018).

Table 1.2. Production of corn in Ukraine's regions in 2014-2018

Regions (oblasts)	Gross harvest (production), kt					Harvested area, 1000 ha					Yield, m.c./ha				
	2014	2015	2016	2017	2018	2014	2015	2016	2017	2018	2014	2015	2016	2017	2018
Vinnytsya	2702.7	1476.9	2574.3	2554.5	3751.4	327.1	299.8	303.9	355.8	378.9	82.6	49.3	84.7	71.8	99.0
Volyn	184.9	119.8	149.1	161.1	288.5	23.9	19.1	21.2	20.6	27.6	77.5	62.8	70.1	78.3	104.3
Dnipro	929.1	1115.8	1197.6	1029.5	1329.7	348.1	296.6	339.2	320.9	309.2	26.7	37.6	35.3	32.1	43.0
Donetsk	366.7	203.6	195.2	210.3	178.5	101.1	65.1	65.9	73.6	60.6	36.3	31.3	29.6	28.6	29.4
Zhytomyr	1292.9	701.1	1171.1	1088.1	1504.7	178.9	144.2	144.2	149.5	165.5	72.3	48.6	81.1	72.8	91.0
Zakarpattia	196.4	193.9	281.7	274.3	272.1	42.9	45.7	51.5	50.5	51.4	45.8	42.4	54.7	54.2	53.1
Zaporizhzhia	130.7	137.8	148.6	136.5	127.7	47.0	39.9	50.9	42.8	36.9	27.8	34.5	29.2	31.9	34.6
Ivano-Frankivsk	355.8	221.3	310.1	291.9	327.3	49.8	38.6	44.5	44.5	43.3	71.5	57.3	69.6	65.6	75.6
Kyiv	2053.3	1466.8	1835.3	1597.1	2828.9	259.1	237.1	247.9	265.3	290.9	79.2	61.9	74.1	60.2	97.2
Kirovohrad	1834.4	1702.8	2071.3	1568.3	2268.7	367.3	324.1	364.6	394.8	373.3	49.9	52.5	56.8	39.7	60.8
Luhansk	316.3	206.4	306.5	181.4	226.5	89.3	77.9	84.3	81.7	65.4	35.4	26.5	36.3	22.2	34.6
Lviv	434.1	244.1	277.0	271.0	358.2	62.2	39.7	39.4	40.0	40.2	69.7	61.5	70.1	67.7	89.2
Mykolaiiv	499.2	428.4	474.5	378.8	571.4	133.9	134.1	121.5	122.8	113.3	37.3	32.0	39.0	30.8	50.4
Odesa	546.0	457.0	609.6	512.5	717.7	162.1	161.3	159.9	154.0	144.4	33.7	28.3	38.1	33.3	49.7
Poltava	3380.1	3636.1	4208.7	2897.7	4927.6	581.8	498.3	543.8	575.0	599.4	58.1	73.0	77.4	50.4	82.2
Rivne	506.3	365.9	520.9	410.1	475.9	61.3	48.9	64.4	60.7	56.0	82.6	74.8	80.8	67.6	84.9
Sumy	2672.7	2336.7	2616.5	2387.9	3273.4	325.5	305.0	314.4	319.7	367.9	82.1	76.6	83.2	74.7	89.0
Ternopil	1188.1	752.9	818.4	861.1	1005.5	153.4	118.5	110.8	108.9	107.6	77.5	63.5	73.8	79.0	93.5
Kharkiv	1606.8	1427.9	1564.1	950.9	1432.5	301.0	264.1	276.5	275.4	254.4	53.4	54.1	56.6	34.5	56.3
Kherson	224.5	200.2	262.3	298.1	293.0	43.3	35.2	40.4	45.0	41.4	51.8	57.0	65.0	66.2	71.0
Khmelnytskyi	1727.4	1120.6	1151.8	1516.1	2101.6	209.6	186.1	153.5	189.8	209.1	82.4	60.2	75.1	79.9	100.5
Cherkasy	2286.8	2106.2	2495.6	1916.1	3363.2	325.8	296.4	330.5	348.8	364.1	70.2	71.1	75.5	54.9	92.4
Chernivtsi	399.7	244.4	254.2	312.4	330.5	63.0	51.2	52.5	60.2	54.1	63.4	47.7	48.4	51.9	61.0
Chernihiv	2661.9	2461.0	2580.2	2863.1	3846.6	369.5	356.6	326.5	380.4	409.3	72.0	69.0	79.0	75.3	94.0
UKRAINE	28496.8	23327.6	28074.6	24668.8	35801.1	4626.9	4083.5	4252.2	4480.7	4564.2	61.6	57.1	66.0	55.1	78.4

1.2. ASSESSMENT OF THE POTENTIAL OF CORN RESIDUES IN UKRAINE

Residues of grain corn production (or corn stover that is a synonym for corn residues) consist of (Fig. 1.5):

- stalks that make up about 52.5% of the whole weight of the residues. At that, the stalk makes up 27.3% of the mass of the whole plant including grain (the same figures are presented below for other parts of corn residues);
- leaves – 20.0 % (10.6%);
- cobs – 17.5% (9.0%);
- wrap of ears – 8.5% (4.3%);
- other parts – 1.5% (0.8%).

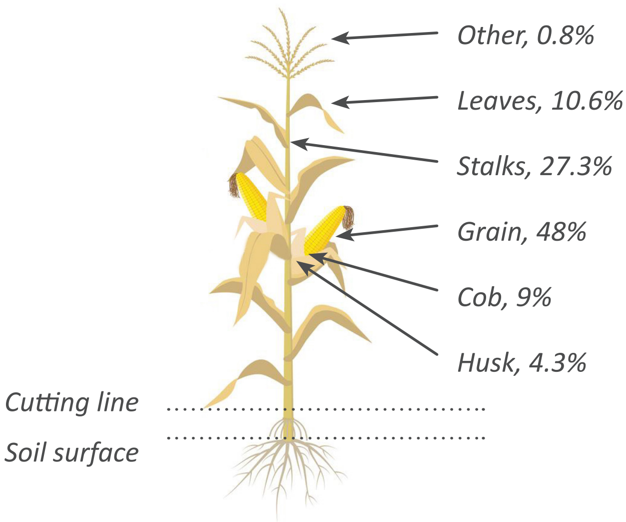
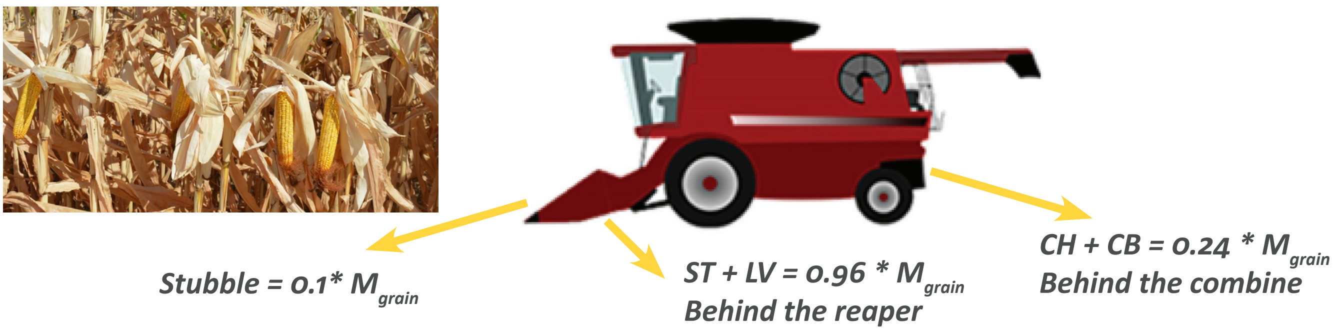


Fig. 1.5. Main parts of corn and their mass ratio[6]

Residue factor (the mass ratio between crop residues and grain of the crop) depends on many factors, primarily on a crop hybrid, but on average, it is 1.3[7]. for corn. When harvesting corn by a combine harvester equipped with a corn reaper, three streams of crop residues are formed by the combine harvester: stubble, stalks, and leaves that remain behind the reaper, and wrap and cobs that remain behind the combine harvester (Fig. 1.6).

Assessment of the corn residues potential available for energy in 2018 based on the approach developed by the Bioenergy Association of Ukraine shows the following results (Table 1.3):

- the theoretic potential (the whole amount of residues generated) is 46.5 Mt or 8.9 Mtoe;
- the economic potential (the amount available for energy, which is 40% of the theoretical potential) is 18.6 Mt or 3.6 Mtoe including stalks – 9.7 Mt (1.9 Mtoe) and cobs – 3.3 Mt (0.6 Mtoe).



ST – stalks, LV – leaves, EW – ear wrap, CB – cob, M_{grain} – mass of grain

Fig. 1.6. Indicative flows of corn residues when harvested with a combine harvester

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[6] L. Kocsis, Z. Hudoba and T. Vojtela. Investigation of the corn stalk gathering for energetic use https://www.yumpu.com/en/document/read/35926184/investigation-of-the-maize-stalk-gathering-for-energetic-use

[7] The value given by Ukraine's National Academy of Agrarian Sciences in its letter to the Institute of Engineering Thermophysics (N 5-2/256 of 16.11.2012)

[8] UABIO Position Paper №7 http://www.uabio.org/img/files/docs/position-paper-uabio-7-ua.pdf

Table 1.3. Potential of corn residues in Ukraine (2018)

Regions (oblasts)	Theoretical potential		Potential available for energy (economic potential)	
	kt	ktoe	kt	ktoe
Vinnytsya	4876.8	931.8	1950.7	372.7
Volyn	375.1	71.7	150.0	28.7
Dnipro	1728.6	330.3	691.4	132.1
Donetsk	232.1	44.3	92.8	17.7
Zhytomyr	1956.1	373.8	782.4	149.5
Zakarpattia	353.7	67.6	141.5	27.0
Zaporizhzhia	166.0	31.7	66.4	12.7
Ivano-Frankivsk	425.5	81.3	170.2	32.5
Kyiv	3677.6	702.7	1471.0	281.1
Kirovohrad	2949.3	563.5	1179.7	225.4
Luhansk	294.5	56.3	117.8	22.5
Lviv	465.7	89.0	186.3	35.6
Mykolaiiv	742.8	141.9	297.1	56.8
Odesa	933.0	178.3	373.2	71.3
Poltava	6405.9	1224.0	2562.4	489.6
Rivne	618.7	118.2	247.5	47.3
Sumy	4255.4	813.1	1702.2	325.2
Ternopil	1307.2	249.8	522.9	99.9
Kharkiv	1862.3	355.8	744.9	142.3
Kherson	380.9	72.8	152.4	29.1
Khmelnytskyi	2732.1	522.0	1092.8	208.8
Cherkasy	4372.2	835.4	1748.9	334.2
Chernivtsi	429.7	82.1	171.9	32.8
Chernihiv	5000.6	955.5	2000.2	382.2
UKRAINE	46541.4	8893.0	18616.6	3557.2

By 2030, one may expect the increase of the potential of corn residues available for energy in Ukraine up to 19.2 Mt/yr or 3.7 Mtoe/yr. It can be explained by the increase of corn yield in Ukraine up to the best indicators of European countries. In 2018, the average yield of corn reached 78.4 centners/ha in Ukraine. Taking into account the current positive dynamics of the development of agriculture in the country, during next 10 years, Ukraine will most probably reach leading EU levels of corn yield.

1.3. CORN RESIDUES STREAMS MAPPING

Production of agricultural residues, including corn residues, is seasonable and depends on harvesting periods. Grain corn is harvested during different time frames, depending on the variety, place of cultivation, and time of sowing. Usually, the time frame for corn harvesting is determined by the level of grain moisture, so before harvesting, they determine the moisture content of the grain and its ripeness, taking into account the terms of sowing and the hybrid ripeness group. By the beginning of harvesting, corn grain must have quite high dry matter content (at least 45%).

As a rule, grain corn is harvested in September-November. For example, in Ukraine in 2016, corn was harvested from 24.4% of the total area by the beginning of October (20.4% of the annual production), and from 65.7% of the area by the beginning of November (61.4% of the annual production) (Fig. 1.7). By December 2, 2016, the share of harvested area under corn came to 95-100% in 10 oblasts, and the rest had the index mainly over 80% (Table 1.4). At that, corn harvesting was carried out faster in the central and southern regions of the country.

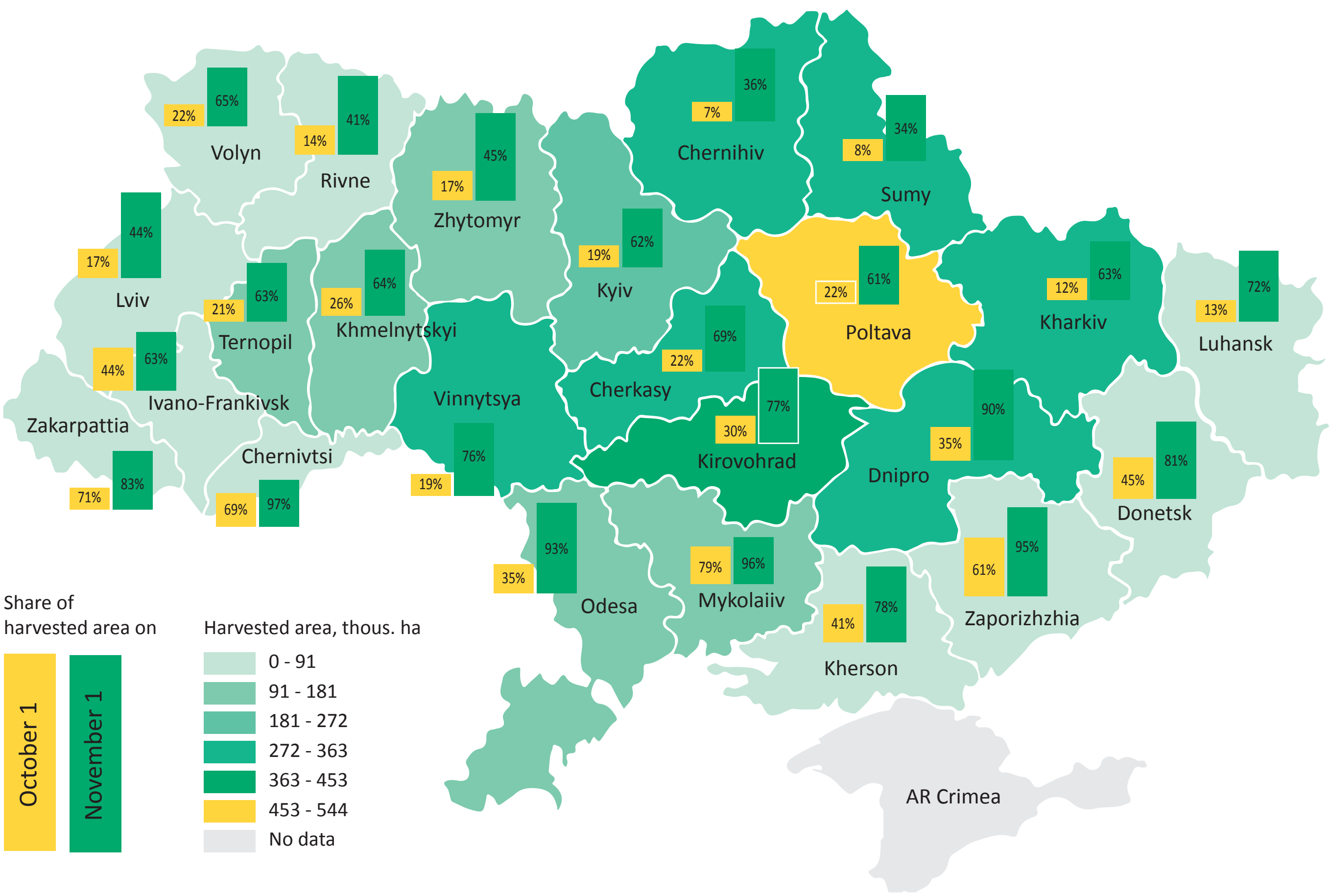

Fig. 1.7. The dynamics of corn harvesting in the regions of Ukraine (2016)[9]

[9] *Report on "Analysis of utilisation of corn straw as an energy source" (2018). Prepared by SEC Biomass for EBRD against Contract C38842/1018/5362.*

Table 1.4. Dynamics of corn harvesting in Ukraine in 2015-2018[10]

Regions (oblasts)	Share of the corn harvested area, %			
	by 15.12.2015	by 02.12.2016	by 08.12.2017	by 14.12.2018
Vinnytsya	100	96	92	100
Volyn	100	95	98	100
Dnipro	100	98	97	100
Donetsk	100	82	98	100
Zhytomyr	100	83	89	93
Zakarpattia	100	100	98	100
Zaporizhzhia	98	100	99	100
Ivano-Frankivsk	100	69	100	95
Kyiv	100	88	86	95
Kirovohrad	100	100	100	100
Luhansk	100	87	96	100
Lviv	96	73	77	100
Mykolaiiv	100	100	95	100
Odesa	100	99	100	100
Poltava	100	71	91	100
Rivne	100	64	67	98
Sumy	95	56	81	95
Ternopil	100	77	83	100
Kharkiv	99	79	96	100
Kherson	100	96	100	100
Khmelnytskyi	100	87	77	100
Cherkasy	100	90	97	100
Chernivtsi	99	98	99	100
Chernihiv	94	72	81	95

It should be noted that in recent years, some farmers have harvested corn in December, January, and even later. However, it is not due to agro-technical requirements but owing to some production needs and economic feasibility. According to the existing harvesting periods, the typical "schedule" of corn residues production is as presented in Table 1.5.

Table 1.5. Seasonable production of corn residues in Ukraine

Month of production	Comments
January	Not typical period (only in cases of some production needs and economic feasibility)
September	Typical period
October	Typical period
November	Typical period
December	Not typical period (only in cases of some production needs and economic feasibility)

[10] *Harvest on-line https://latifundist.com/urozhaj-online-2018*

Distribution of the corn residues potential over Ukraine's territory is not even. Regions with the highest concentration of this type of biomass are oblasts with the biggest production volumes of grain corn. For 2018, they are Poltava oblast (with the economic potential of corn residues of 489.6 ktoe), Chernihiv oblast (382.2 ktoe), and Vinnytsia oblast (372.2 ktoe) (Fig. 1.8).

Fig. 1.8. Economic potential of corn residues for energy in Ukraine's regions (2018)

1.4. FUEL CHARACTERISTICS AND PROPERTIES OF CORN RESIDUES

Generally speaking, corn residues have quite good fuel properties, which are close to those of wood fuel. Due to that, biofuels made from corn residues can be burnt in the equipment intended for wood biomass. Detailed characteristics and fuel properties of different types of corn residues are presented in Table 1.6. A comparison of the properties with those of other agricultural residues and wood chips is shown in Table 1.7.

Ash content of corn stover is the main 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 nonstructural[11]. Structural ash consists of inorganic substances of a crop, which remain after its burning. The usual ash content of corn straw is 3.5%. Unstructured ash is inorganic substances (mostly soil) that get into biomass during harvesting, in particular when forming swaths and baling. The typical total ash content for multiple passes of agricultural machines during harvesting is 8-10%.

[11] *Brittany Schon, Matt Darr. Corn Stover Ash. https://store.extension.iastate.edu/Product/Corn-Stover-Ash*

Table 1.6. Characteristics and fuel properties of corn residues[12]

Parameters	Samples of corn stalks and leaves[1)]			Samples of corn cobs[1)]		
	#704	#889	#1241	#2068	#2791	#1454
Proximate analysis:						
Moisture content, W^{ar}, %	6.06	5.00	–	–	7.04	–
Ash content, A^{d}, %	5.06	7.35	5.58	3.48	3.12	3.60
Volatile matter, V^{daf}, %	85.17	84.30	79.61	–	80.69	83.20
Ultimate analysis:						
Carbon, C^{d}, %	46.82	46.50	43.65	48.22	46.51	45.31
Hydrogen, H^{d}, %	5.74	5.81	5.56	6.20	5.68	7.16
Nitrogen, N^{d}, %	0.66	0.56	0.61	1.57	0.47	–
Sulphur, S^{d}, %	0.11	0.11	0.01	0.13	0.09	–
Oxygen, O^{d}, %	41.36	39.67	43.31	42.94	44.13	43.93
Halides:				#1240[5)]		
Halides, Cl^{d}, mg/kg	2661.3	0.0	6000.0	2100	–	–
Net calorific value, Q^{ar}, MJ/kg	15.68	16.72	16.44[4)]	–	15.05	14.02[4)]
Gross calorific value, Q^{daf}, MJ/kg	19.06	20.50	18.69	19.95[2)]	18.19	16.16
Ash composition, %:				#402[3)]		
P_2O_5	8.68	–	–		–	–
SiO_2	54.04	–	–		–	–
Al_2O_3	1.99	–	–		–	–
CaO	8.66	–	–		–	–
MgO	6.11	–	–		–	–
Na_2O	0.15	–	–		–	–
K_2O	20.67	–	–		–	–
Ash melting behavior, °C:				#402[3)]		
Initial deformation temperature (IDT)	–	1232	–	900	–	850
Hemispherical temperature (HT)	–	1500	–	–	–	1000
Fluid temperature (FT)	–	1500	–	1020	–	–
Biochemical composition, %			#2372[7)]		#979[6)]	
Cellulose	–	36.80	28.00	26.30	52.00	–
Hemicellulose	–	25.40	28.00	25.20	32.00	–
Hemicellulose	–	16.90	11.00	16.30	15.00	–

Upper indexes: ^{ar} – fuel as received; ^{d} – dry matter; ^{daf} – dry and ash free basis.

1) Numbers according to Phyllis database. 2) HHV_{Milne}. 3) Ash composition and ash melting behavior for sample #402. 4) For dry matter. 5) Halides for sample #1240. 6) Biochemical composition for sample #979. 7) Biochemical composition for sample #2372.

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[12] Phyllis database containing information on the composition of biomass and waste https://phyllis.nl/

Table 1.7. Chemical composition and some properties of different types of biomass

Parameters	Yellow straw	Gray straw	Winter wheat straw	Corn stalks*	Sunflower stalks*	Wood chips
Moisture content, %	10-20	10-20	11.2	45-60 (after harvesting) 15-18 (air dried)	60-70% (after harvesting) ~20 (air dried)	40
Net calorific value, MJ/kg	14.4	15	14.96	16,7 (d.m.) 5-8 (W 45-60%) 15-17 (W 15-18%)	16 (W<16%)	10.4
Volatile matter, %	>70	>70	80.2	67	73	>70
Ash content, %	4	3	6.59	6-9	10-12	0.6-1.5
Ultimate analysis, %:						
Carbon	42	43	45.64	45.5	44.1	50
Hydrogen	5	5.2	5.97	5.5	5.0	6
Oxygen	37	38	41.36	41.5	39.4	43
Chlorine	0.75	0.2	0.392	0.2	0.7-0.8	0.02
Potassium (alkali metal)	1.18	0.22	–	corn cobs: 6.1 mg/kg d.m.	5.0	0.13-0.35
Nitrogen	0.35	0.41	0.37	0.69; 0.3	0.7	0.3
Sulphur	0.16	0.13	0.08	0.04	0.1	0.05
Ash melting temperature, °C	800-1000	950-1100	1150	1050-1200	800-1270	1000-1400

d.m. – dry matter; W – moisture content.
** Data for volatile matter, ash content, and ultimate analysis are based on dry matter.*

As for ash melting behaviour, corn stover is close to wood biomass, which provides better conditions for combustion compared to straw of cereal crops. For comparison: ash melting temperature for wood is about 1200 °C, and that of corn stalks is about 1100 ºC (see Table 1.7). In addition, corn straw contains less chlorine (0.2% d.m.) compared with fresh («yellow») straw of spiked cereal crops (0.75% d.m.). It is a positive factor for corn residues as fuel as chlorine compounds cause corrosion of steel elements of energy equipment.

The elemental composition of corn stover is almost the same as for straw of spiked cereal crops, so they have almost the same calorific value. The properties of crop residues strongly depend on the place of cultivation, harvesting time, weather, type of soil, and fertilizers. The moisture content has the most significant effect on the calorific value of corn residues (Fig. 1.9).

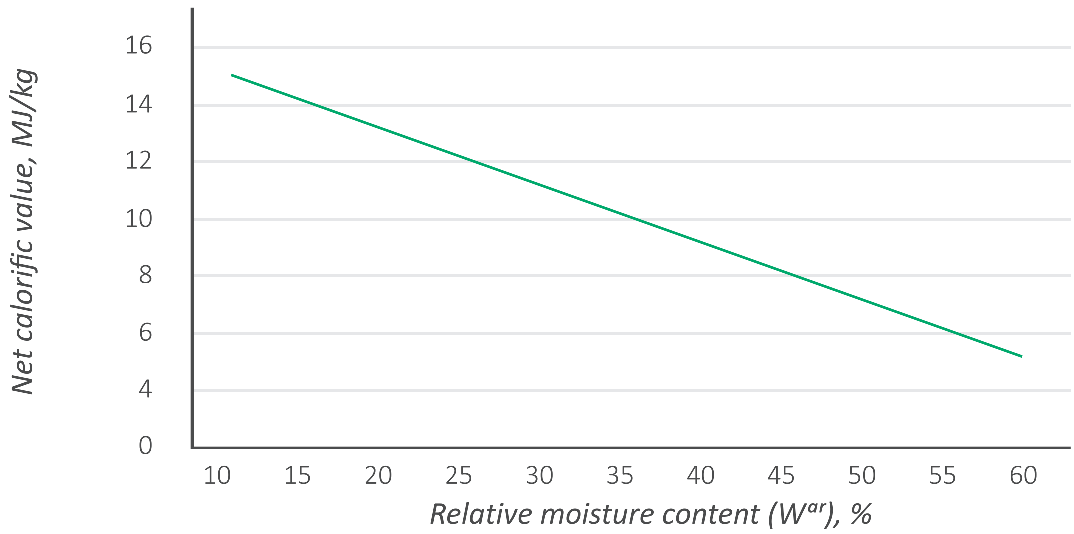

Fig. 1.9. Net calorific value depending on the moisture content of corn stover (as-received basis)

2

ESTABLISHING OF SUPPLY CHAINS FOR CORN RESIDUES

2.1. SELECTION OF TECHNOLOGY FOR HARVESTING CORN AND CORN RESIDUES

There are several technological schemes for harvesting grain corn:

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

Currently, the main method for the harvesting of commercial corn is **combine threshing of ears in the field, shredding and spreading of the cut biomass** with the use of combine harvesters equipped with corn reapers. This method of harvesting grain corn is the most economically feasible. In comparison with harvesting ears, the method provides 1.8-2 times decrease in labor costs and 20-25% reduction in fuel consumption[13]. Only a few agricultural enterprises (seed factories) collect corn as non-threshed ears with the following stationary threshing, which makes it possible to collect cobs. The seed factories grow corn to obtain (hybrid) corn seeds as planting stock. The collection of a mixture of grain and cobs with combines is not widespread in Ukraine yet. When harvesting corn with a combine harvester equipped with a corn reaper, the plant remains are redistributed as follows (Fig. 1.6): stubble remains (10% of the grain mass), remains behind the combine reaper (96% of the grain mass) and remains behind the combine harvester (24% of the grain mass).

Pressing biomass into bales by raw material compacting of more than 4 times contributes to increased logistics efficiency and reduces the required

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[13] Cherenkov A.V., Tsykov V.S., Dziubetskyi B.V., Shevchenko M.S. and other. 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.

area of warehouses. Technological schemes for **harvesting corn stover (corn residues) in bales** can be divided into 4 main types:

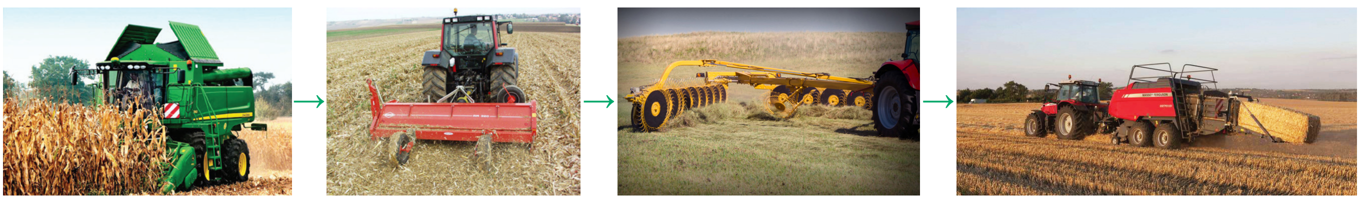
1. Single-pass harvesting system: a baler is attached to the combine harvester, which allows to form corn residues bales simultaneously with grain threshing (Fig. 2.1a).
2. Two-pass system: the combine harvester with a reaper that forms a corn windrow, which is then baled with a baler attached to the tractor (Fig. 2.1b).
3. Three-pass system: combine harvester + tractor with stalk-shredding widrower + tractor with a baler for large square bales (round bales) (Fig. 2.1c).
4. Multi-pass system: combine harvester + tractor with mulcher + tractor with rake + tractor with a baler (Fig. 2.1d).

Of these technologies, for Ukraine we recommend the three-pass system (Fig. 2.1c) due to the possibility to use standard machinery available for agricultural producers and due to less contact of biomass with the soil.

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

Fig. 2.1. Technological schemes for corn stover harvesting[14]

[14] *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*

Different models of equipment can be used at different stages of the harvesting process (Fig. 2.2). Not all the types of required equipment are available in the Ukrainian market, but they can be ordered and imported through dealers in Ukraine.

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

Fig. 2.2. Models of farm machinery for corn stover harvesting

An example of the baled corn residues whole supply chain is presented in Fig. 2.3. It is the supply chain implemented and used by the DuPont company (the USA) to provide its cellulosic ethanol plant with feedstock. Corn is harvested by local farmers while other operations are carried out by the plant staff.

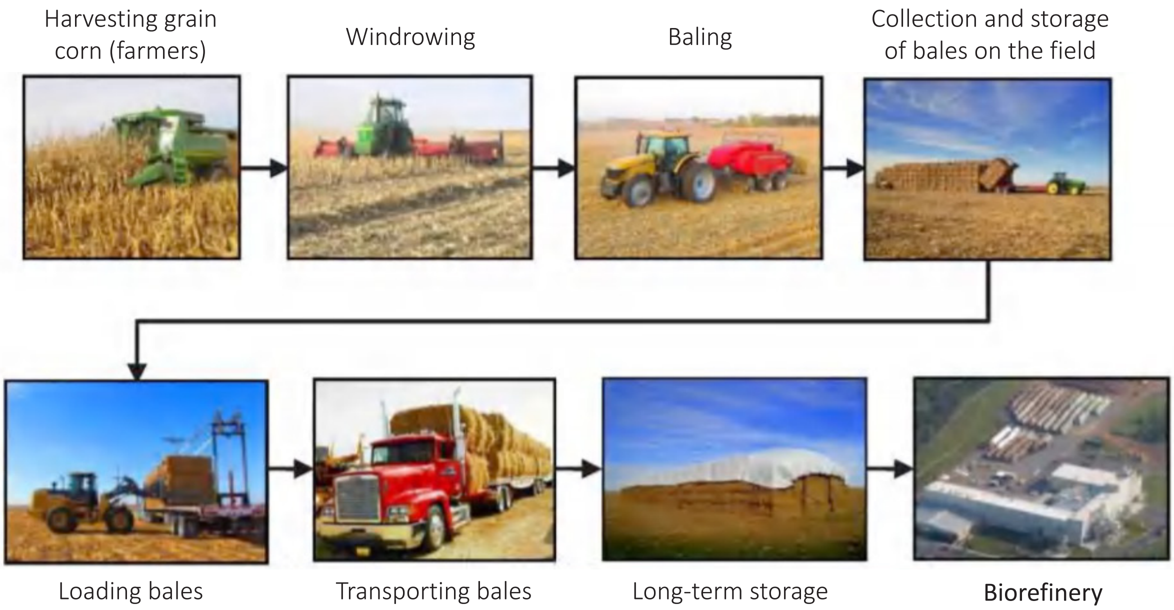


Fig. 2.3. DuPont's cellulosic ethanol plant model for corn stover supply chain[15]

[15] 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

In addition to the technology of corn residues harvesting in square bales, the biomass can be baled in round bales using a round baler instead of a large square baler or it can be shredded as a mixture of different fractions of corn residues or selected fractions such as cobs. The flow charts for the harvesting of shredded corn residues with a forage harvester or a forage loader wagon, which are used for silage corn harvesting, are shown in Fig. 2.4. In accordance with the results of field experiments in the Bavarian State Research Centre for Agriculture in 2014 and 2015, the ash content of corn stover was 7.0±1.9% d.m. for forage harvester and 6.9±2.0% d.m. for forage loader wagon[16].

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

Fig. 2.4. Shredded corn stover supply chains

Another option for corn residues harvesting is the collection of a part of residues after threshing grain with a combine harvester. For example, in 2018, researchers from the Italian company CREA-IT (Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria) carried out some on-field experiments to assess the performance of an innovative mechanized system for the collection of corn cobs[17] (Fig. 2.5a). Using the combine harvester with the Harcob system, it was possible to harvest on average 2 t/ha of cobs with the biomass productivity of 4.1 t/hr[18]. The Vermeer Company produces the harvester machine CCX770 for cobs (Fig. 2.5b) that is available on the market[19]. The Vermeer CCX770 cobs harvester is a pull-type collection wagon attached to the combine harvester. This machinery enables farmers to harvest separately corn grain and corn cobs in one pass.

[16] *Monika Fleschhut, Kurt-Jurgen Hulsbergen, Stefan Thurner, Joachim Eder Analysis of different corn stover harvest systems / LANDTECHNIK, 71 (6), 2016. – 252-270 p.*
[17] *https://www.becoolproject.eu/2018/10/22/recovering-maize-cob-converting-untapped-biomass-resource-into-valuable-feedstock/*
[18] *http://www.etaflorence.it/proceedings/?detail=15215*
[19] *https://www.vermeer.com/NA/en/N/equipment/cob_harvester*

a) *b)*

Fig. 2.5. Cob harvesters: a) – Harcob system; b) – Vermeer CCX770

Various technologies based on different machinery can be used for corn residues harvesting. However, taking into account equipment available on the market and results of field trials in the USA and the EU, it is reasonable to perform the technical and economic assessment of four corn stover supply chains:

1) **SC1** – the three-pass system on the basis of a large square baler: combine + tractor with stalk-shredding windrower + tractor with large square baler (Fig. 2.1c);

2) **SC2** – the three-pass system on the basis of a round baler: combine + tractor with stalk-shredding windrower + tractor with round baler;

3) **SC3** – forage harvester system: combine +tractor with stalk-shredding windrower + forage harvester + tractor with trailer (Fig. 2.4a);

4) **SC4** – forage wagon system: combine + tractor with stalk-shredding windrower + tractor with forage loader wagon (Fig. 2.4b).

In addition, the corn cob harvesting technology on the basis of Vermeer CCX770 cob harvester (Fig. 2.5b) will be assesed.

2.2. FEASIBILITY STUDY OF CORN RESIDUES HARVESTING

Cost-effectiveness of corn residues harvesting depends on the capital cost of machinery and operating costs, which vary according to the specific mass of harvested biomass per unit area of the field, productivity of machines, distance of the harvested biomass transportation from the field to the central storage facility.

From the practical experience, farmers harvest from 2.5 to 5 t d.m. of corn residues from a hectare in the USA. In general, it is possible to assume the collection efficiency of corn stover as 50%. Corn stover yield from a hectare as a function of the yield of corn grain with 14% basic moisture content is given in Fig. 2.6.

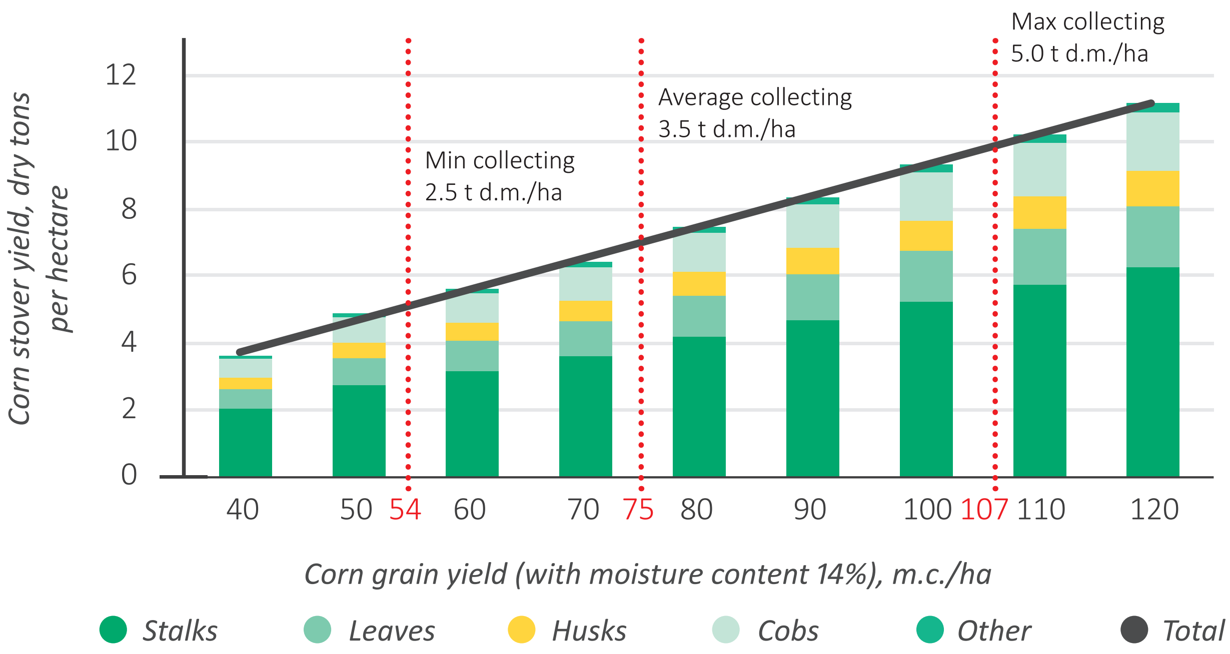


Fig. 2.6. Corn stover yield in dry tons

In the following calculations, we consider three scenarios of biomass harvesting:

- minimum – harvesting of 2.5 t d.m./ha;
- average – harvesting of 3.5 t d.m./ha;
- maximum – harvesting of 5.0 t d.m./ha.

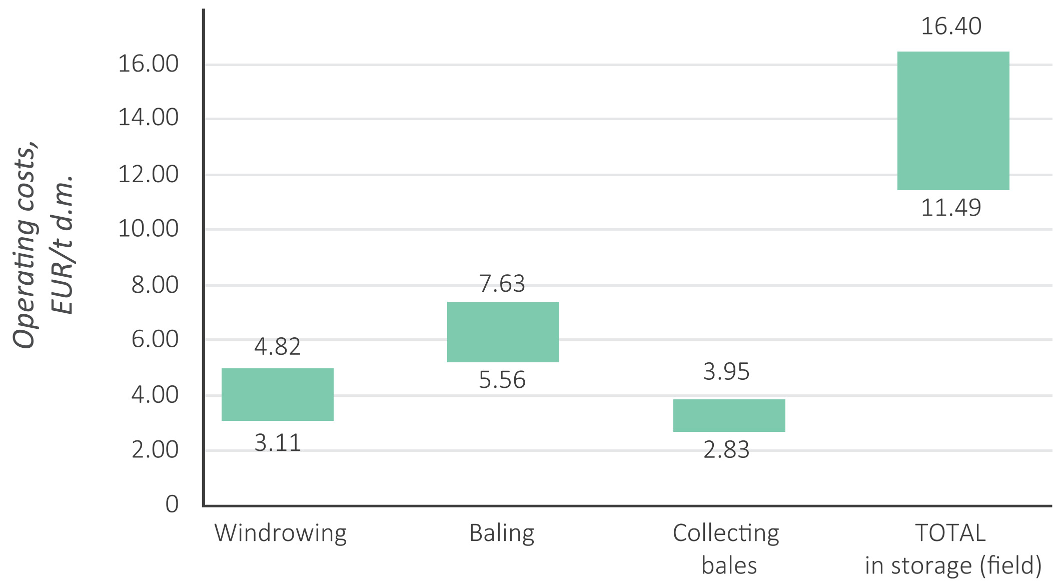
The approximate cost of machinery related to the corn residues harvesting by the three-pass system based on the large square baler is shown in Table 2.1. Conditional cost is a part of the actual cost that depends on the operating period of the equipment during a year.

Operating costs of harvesting corn stover in the square bales are shown in Fig. 2.7. It can be seen that operating costs considerably depend on the weight of corn residues harvested from the field.

The operating costs also depend on the distance of transportation of bales from the field to the central storage facility, which is shown in Fig. 2.8. A considerable increase in the costs can be observed at a distance of transpoprtation of over 100 km.

Table 2.1. Capital cost of the machinery required for the harvesting of corn stover in square bales (SC1) with 20-35 t/h productivity

Process	Equipment	Unit price, 1000 EUR	Qty	Cost, 1000 EUR	Use of equipment, % of the annual usage			Conditional cost, 1000 EUR		
					Min	**Avg**	Max	Min	**Avg**	Max
Harvesting and storage at the local store place (near the field)	**1. Windrowing**	**138.5**	**1**	**138.5**				**59**		
	Tractor NH T7060	102	1	102	21.9			22.3		
	Shredder Hiniker 5620	36.5	1	36.5	100			36.5		
	2. Baling	**297**	**1**	**297**				**102**		
	Tractor Deutz-Fahr X 720	135	1	135	15.6			21		
	Baler MF 2270	162	1	162	50			81		
	3. Collecting and stacking bales	**201.5**	**1**	**201.5**				**66**		
	Tractor NH T7060	102	1	102	15.6			15.9		
	Trailer Arcusin XP 54 T	99.5	1	99.5	50			49.8		
Transporting to the main storage	**4. Loading bales**									
	Telehandler MF9407	**71**	**1**	**71**	19.8	**24.3**	29.7	14	**17**	22
	5. Transportation at a distance of 25-50 km									
	Track MAZ with a semitrailer	**80**	**4**	**320**	6.6	**8.1**	9.9	21	**26**	32
TOTAL				**1028**				262	**270**	279
Total, items 1-4				**708**						



Upper values are for the harvesting of 2.5 t d.m./ha (3920 t d.m./yr).
Lower values are for the harvesting of 5 t d.m./ha (5880 t d.m./yr).

Fig. 2.7. Operating costs at different stages of corn stover harvesting in the form of square bales

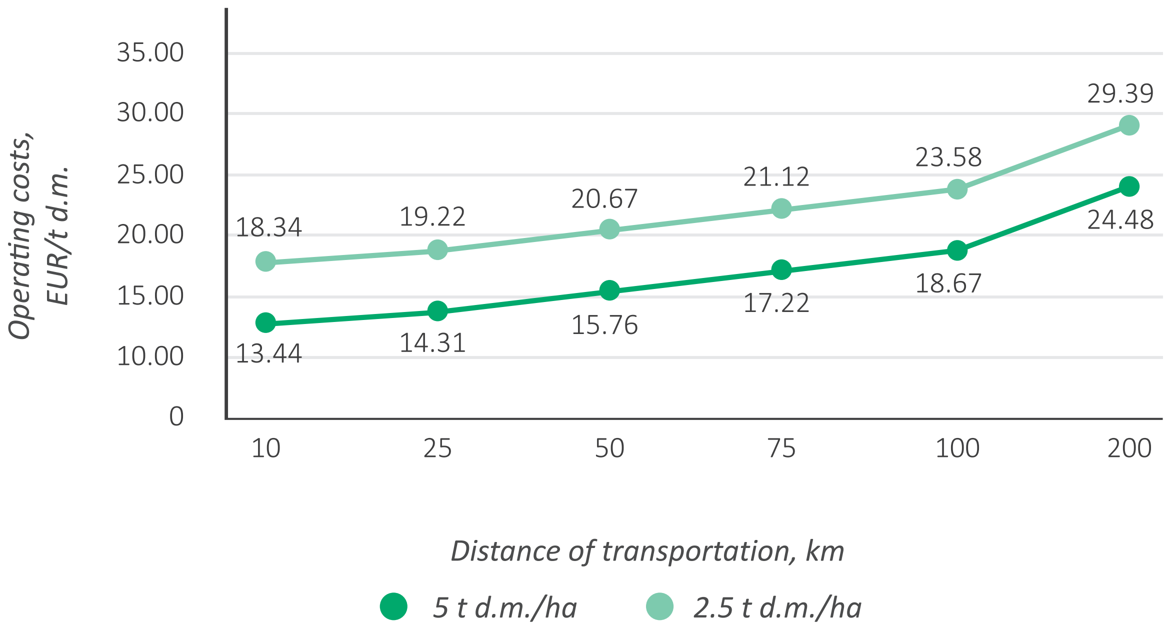


Fig. 2.8. Operating costs of corn residues harvesting as a function of the distance of transportation

Comparison of average production costs of big rectangular bales from corn stover by technological operations in Iowa State (the USA) and Ukraine shows that they are roughly equal for both countries: 19.37 EUR/t d.m. for the USA and 16.40 EUR/t d.m. for Ukraine. However, labor costs in the USA are 4.3 times higher than in Ukraine (Table 2.2).

Table 2.2. Production costs of big rectangular bales from corn stover in the USA and Ukraine

Technological operations	Expense items*, EUR/t d.m.					Sum, EUR/t d.m.
	Amortization	**Repairs**	**Fuel**	**Materials**	**Labor**	
1. Windrowing	3.05 / 1.50	0.78 / 0.75	1.85 / 2.38		0.86 / 0.19	6.54 / 4.82
2. Baling	4.33 / 2.60	1.08 / 1.30	1.65 / 2.16	1.04 / 1.43	0.62 / 0.14	8.72 / 7.63
3. Collecting bales	2.03 / 1.68	0.72 / 0.84	0.92 / 1.33		0.43 / 0.11	4.11 / 3.95
TOTAL	**9.41 / 5.78**	**2.58 / 2.89**	**4.42 / 5.87**	**1.04 / 1.43**	**1.91 / 0.44**	**19.37 / 16.40**

** In the table, the first figures are for the USA (recalculated from data PM 3053B, Edwards, 2014, Iowa State University). Second figures (after the slash) are for Ukraine for 2.5 t d.m./ha productivity of corn stover harvesting.*

Assessments of production cost for the other three technologies of corn stover harvesting (in round bales, shredded by a forage harvester and by a forage loader wagon) were done for the average scenario with the harvesting of 3.5 t d.m./ha. The capital cost of machinery related to the harvesting of corn residues for the SC2, SC3, and SC4 supply chains is given in Tables 2.3-2.5. The transportation distance from the field to the main storage is up to 25 km for the round bales and the forage loader system, and 10 km for the forage harvester system, which uses one transportation step from the field to the main storage facility without a local storage near the field.

Technological operations of the supply chain of corn stover in round bales are similar to ones for large square bales, but a round baler is less productive. The dimensions of the round bale are: 1.5 m diameter and 1.22 m width. Bale net wrap is used for the shredded corn stover wrapping. The average mass of 345 kg of dry matter in the round bale is assumed in calculations. The accepted productivity of the technology is 8-10 t/h.

Table 2.3. Capital cost of the equipment required for the corn stover harvesting in round bales (SC2) with 8-10 t/h productivity

Process	Equipment	Unit price, 1000 EUR	Qty	Cost, 1000 EUR	Use of equipment, % of annual usage	Conditional cost, 1000 EUR
Harvesting and storage at the local store place (near the field)	**1. Windrowing**	**138.5**	**1**	**138.5**		**44.8**
	Tractor NH T7060	102	1	102	8.2	8.3
	Shredder Hiniker 5620	36.5	1	36.5	100	36.5
	2. Baling	**130**	**1**	**130**		**34.1**
	Tractor Claas Arion 640	90	1	90	15.6	14.1
	Baler Claas Rollant 620	40	1	40	50	20
	3. Collecting and stacking bales	**120**	**1**	**120**		**28.9**
	Tractor Claas Arion 640	90	1	90	15.6	14.1
	Trailer Kobzarenko PT-30	30	1	30	50	14.8
Transporting to the main storage	**4. Loading bales**					
	Telehandler MF9407	**71**	**1**	**71**	**11.8**	**8.4**
	5. Transportation*					
	Track MAZ with a semitrailer	**80**	**2**	**160**	**6.9**	**11.0**
TOTAL				**619.2**		**127.2**
Total, items 1-4				**459.2**		

** The distance from the local storage place to the main storage is up to 25 km.*
*** Capital cost of the equipment in case of availability of trucks for the transportation of bales.*

A self-propelled forage harvester is widely used for harvesting corn silage. Farmers dealing with cattle breeding can use their equipment for harvesting corn stover. For the transportation of shredded corn stover simultaneously with forage harvesting, it is necessary to use a lot of tractors with trailers due to the low density of shredded biomass and high productivity of the harvester. In this case, the transport distance is up to 10 km.

The forage loader system is based on the use of the special machine attached to a tractor, which can pick-up shredded corn stover from a windrow, compress the biomass and then transport it to a local storage facility. From the local storage facility, the biomass is loaded with a telehandler or frontal loader to a vehicle with a high capacity trailer for transportation to the main storage.

Table 2.4. Capital cost of equipment required for the harvesting of shredded corn stover with a forage harvester (SC3) with 20-40 t/h productivity

Process	Equipment	Unit price, 1000 EUR	Qty	Cost, 1000 EUR	Use of equipment, % of annual usage	Conditional cost, 1000 EUR
Harvesting and transporting to the main storage	**1. Windrowing**	**138.5**	**1**	**138.5**		**60.8**
	Tractor NH T7060	102	1	102	23.9	24.3
	Shredder Hiniker 5620	36.5	1	36.5	100	36.5
	2. Harvesting	**240**	**1**	**240**		**120**
	Forage harvester Claas Jaguar 850	240	1	240	50	120
	3. Transportation*	**177**	**7**	**1238.1**		**311.4**
	Tractor Claas Axion 850	125	7	875	14.8	129.9
	Trailer Kobzarenko TZP-39	51.9	7	363.1	50	181.6
TOTAL				**1616.6**		**492.3**

** The distance from the field to the main storage is up to 10 km.*

Table 2.5. Capital cost of equipment required for the harvesting of shredded corn stover with a forage loader wagon (SC4) with 10-20 t/h productivity

	Equipment	Unit price, 1000 EUR	Qty	Cost, 1000 EUR	Use of equipment, % of annual usage	Conditional cost, 1000 EUR
Harvesting and storage at the local store place (near a field)	**1. Windrowing**	**138.5**	**1**	**138.5**		**49.7**
	Tractor NH T7060	102	1	102	12.9	13.2
	Shredder Hiniker 5620	36.5	1	36.5	100	36.5
	2. Harvesting	**224**	**1**	**224**		**69.0**
	Tractor Claas Axion 850	125	1	125	15.6	19.5
	Feeding wagon Claas Cargos 8400	99	1	99	50	49.5
Transporting to the main storage	**3. Loading**					
	Telehandler MF9407	71	1	71	14.5	10.3
	4. Transportation*					
	Track MAZ with a semitrailer	105	3	315	9.5	9.9
TOTAL				**748.5**		**139.0**
Total, items 1-4				**433.5**		

** The distance from the local storage place to the main storage is up to 25 km.*
*** Capital cost of the equipment in case of availability of trucks for the transportation of bales.*

The cost estimation of corn residues harvesting by four technologies (in large square bales, round bales, in a shredded form on the basis of a forage harvester and forage loader wagon) was carried out according to an average scenario of harvesting of 3.5 t d.m./ha. The diagrams with shares of operating costs (labor, fuel, materials, repairs, and amortization) for these three technologies of corn stover harvesting are shown in Fig. 2.9. The amortization and fuel are the main costs in the value chains.

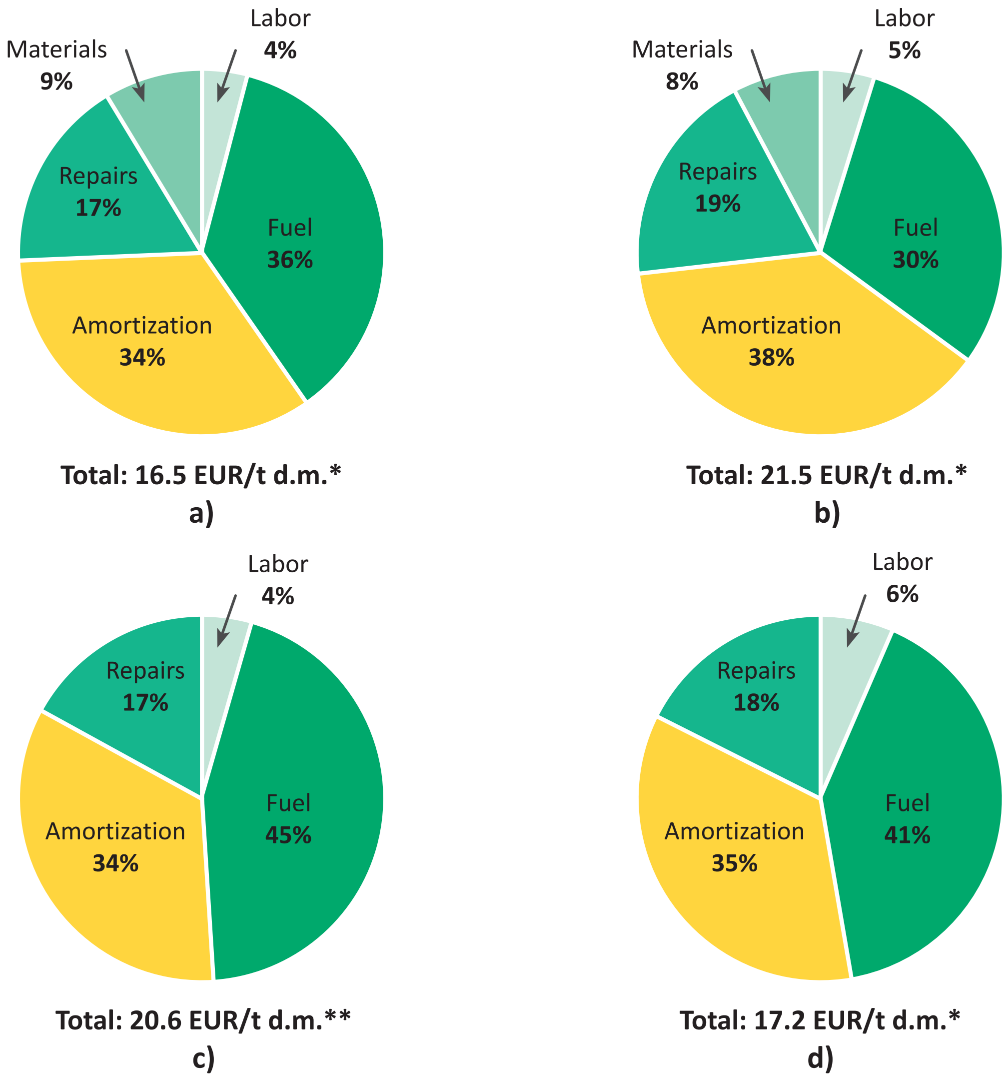


Fig. 2.9. Cost of corn residues harvesting in the amount of 3.5 t d.m./ha with their transportation to the main storage:

a) large square baler; b) round baler;
c) forage harvester; d) forage loader wagon.

*Notes: * Distance of transportation is 25 km*
*** Distance of transportation is 10 km*

Cost comparison for all harvesting technologies for the harvesting of 3.5 t d.m./ha depending on the distance of transportation is given in Fig. 2.10. The harvesting of corn stover in large square bales with their transportation at a distance more than 20 km is economically feasible. For the smaller distance, the forage loader wagon can be used.

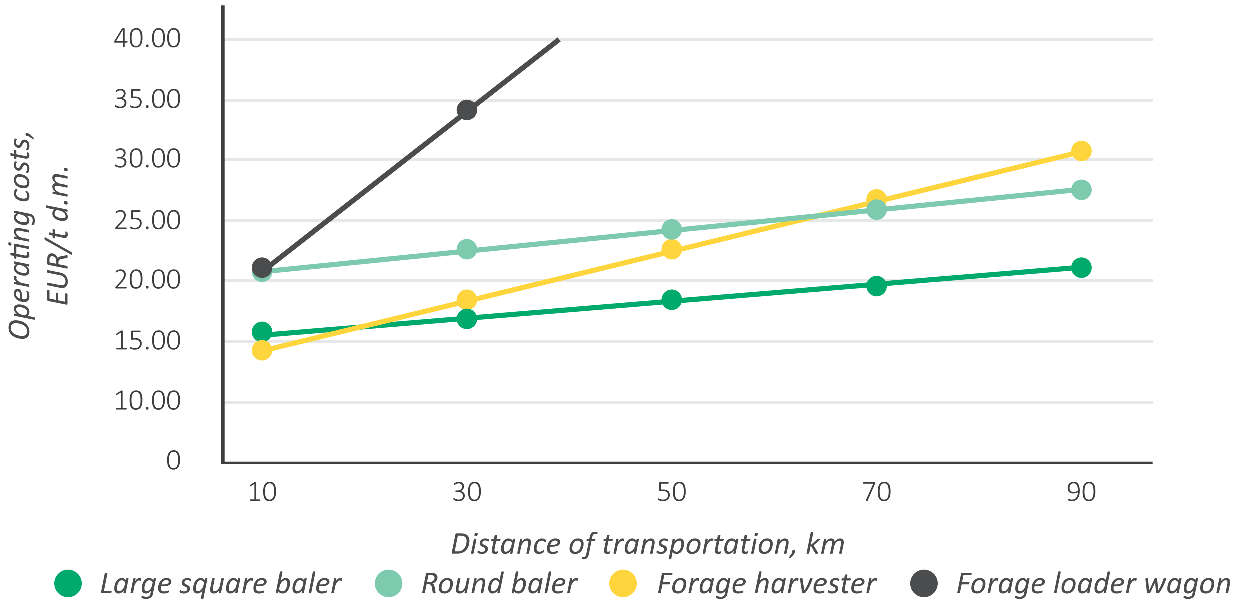


Fig. 2.10. Operating costs for the harvesting technologies as a function of the distance of transportation

Results of a feasibility study on corn stover harvesting in the square bales are presented in Table 2.6. The payback period of crop residues harvesting projects significantly depends on the weight of biomass harvested per hectare, which also affects the loading of machinery. Thus, when harvesting corn stover of 2.5 t d.m./ha, the simple payback period of the harvesting team based on one large square baler is 6.4 years, and it is 3.7 years when harvesting corn residues of 5 t d.m./ha. In the average scenario of the biomass harvesting of 3.5 t d.m./ha, which can be achieved with a corn yield of 75 m.c./ha, the simple payback period of such harvesting team is 4.8 years.

Table 2.6. Techno-economic assessment of harvesting corn stover in the square bales (SC1)

Indicators	**Corn residues output**		
	2.5 t d.m./ha	**3.5 t d.m./ha**	**5 t d.m./ha**
Productivity of biomass harvesting, t d.m./yr	3920	**4802**	5880
Capital costs, thous. EUR	261.7	**269.6**	279.3
Operating costs, thous. EUR/yr	80.5	**90.7**	103.3
Loan (the share of capital costs), %	60		
Loan rate, %	7		
Corn stover price*, EUR/t d.m.	8.0		
Net cost of biomass bales**, EUR/t d.m.	27.2	**24.5**	22.3
Sale price of biomass bales***, EUR/t d.m. with VAT	40		
Simple payback period, yr	6.4	**4.8**	3.7
Discounted payback period (under discount rate of 7%), yr	8.7	**5.8**	4.2
IRR, %	12.3	**22.5**	35.1

** The price is determined by the cost of the equivalent amount of mineral fertilizers required to replace the nutrients taken away with the biomass from the field.*

*** The cost includes direct costs for harvesting biomass and deductions for equipment amortization.*

**** The price is equal to the sale price of biomass bales (W25%) of 25 EUR/t without VAT.*

The initial data concerning the use of the cob harvester is taken from the Purdue extension paper ID-417-W[20]. Due to the additional weight of the CCX770, the productivity of the combine decreases by 10%, and this is taken into account in the calculations of operating costs. The yield of corn cobs is 1.25 t d.m./ha. The transportation distance of corn cob is 10 km. The average annual cob harvesting period is 40 days.

The results of the techno-economic assessment of corn stover harvesting in round bales, shredded form based on a forage harvester and a forage loader wagon and machines for harvesting cobs are given in Table. 2.7.

From the considered options, the lowest cost of biomass is 25.2 EUR/t, which corresponds to the harvesting with SC4 technology using a forage loader wagon. When using a round baler (SC2), the cost of biomass is 29.5 EUR/t; self-propelled forage harvesters allow to obtain a corn stover cost of 28.6 EUR/t, and when harvesting cobs by a specialized harvester, the biomass cost is 34.9 EUR/t. At the same time, the higher selling price of the collected corn cobs than for corn stover is accepted because cobs can be used without further processing.

Table 2.7. Techno-economic assessment of different corn stover harvesting technologies

Indicators	Harvesting technology			
	Round baler (SC2)	Forage harvester (SC3)	Forage wagon (SC4)	Cob harvesting
Output of corn residues, t d.m./ha	3.5	1.25		
Productivity of biomass, t d.m./yr	1551	5390	2924	500
Capital costs, thous. EUR	127.2	492.3	139.0	85.2
Operating costs, thous. EUR/yr	33.0	116.5	55.9	8.9
Loan (the share of capital costs), %	60			
Loan rate, %	7			
Corn stover price in the field*, EUR/t d.m.	8.0	-		
Net cost of biomass bales**, EUR/t d.m.	29.5	28.6	25.2	34.9
Sale price of corn stover*** or cobs****, EUR/t d.m. with VAT ***	40***	70****		
Simple payback period, yr	9.4	8.7	4.6	6.7
Discounted payback period (under discount rate of 7%), yr	>10	>10	5.3	8.8
IRR, %	1.7	3.3	26.0	12.6

** The price is determined by the cost of the equivalent amount of mineral fertilizers required to replace the nutrients taken away with the biomass from the field.*

*** The cost includes direct costs for harvesting biomass and deductions for equipment amortization.*

**** The price is equal to the sale price of biomass bales (W25%): 25 EUR/t without VAT.*

***** The price is equal to the sale price of cobs (W20%): 40 EUR/t without VAT.*

[20] https://www.extension.purdue.edu/extmedia/ID/ID-417-W.pdf

Thus, according to the obtained results, the most economically feasible technology of corn stover harvesting is the use of **large square bales** that will allow to obtain biomass in the central storage facility at a distance of 25 km from the field at a cost of 22.3 EUR/t d.m. The system of harvesting shredded corn residues based on a forage loader wagon is also economically feasible with a simple payback period of 4.6 years and IRR of 26.0%. However, field research is needed to evaluate the feasibility of using this technology under Ukrainian conditions. For biomass processing, it is important to make a technical and economic assessment of the full value chain, including storage. Further processing of corn stover into briquettes and pellets will increase the added value of biomass.

2.3. CORN RESIDUES STORAGE COSTS

Corn stover should be stored under the conditions of keeping its normal amount of moisture against rain and soaking from the ground, avoiding decay and ensuring protection against fire. The selection of a storage type depends on location and local conditions. The corn stover can be stored in an open storage, tarped storage, permanent structure storage, or anaerobic storage . Several factors should be considered when selecting appropriate storage systems: feedstock stability during storing, cost of storage infrastructure, accessibility of feedstock during the entire storage duration, integration of the storage with a processing plant.

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 a new storage building, the permanent storages are economically unfeasible. In the 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. Also, it can be used as the main storage facility in some regions. However, it is necessary to do it very carefully due to possible losses of dry matter of biomass.

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[21].

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 on the surface, which prevents the formation of fungus and mold. The agrofibre is used for wood chips drying. The period of agrofibre usage is more than 5 years[22]. The corn stover tarped storage with agrofibre was chosen for further cost assessment.

The corn stover storage facilities have to be arranged according to the Fire Safety Regulations in Agricultural Sector of Ukraine (Order of Ministry of agriculture and Ministry of emergency situation #730/770)[23]. 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 distance not less than 6 m between stacks in pair and not less than 30 m between adjacent double stacks.

It is essential to secure free access to biomass for the loaders. 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 associated with feedstock losses through dry matter loss. The costs assessment of tarped storage for shredded, large square bales, and round bales of corn stover are given in Table 2.8. The guard costs aren't taken into account due to the assumption that the main corn stover storage facility will be placed near the farmer`s storage facility with an existing guard system.

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[21] *https://store.extension.iastate.edu/product/14077*
[22] *http://zavod-kobzarenko.derevo.ua/catalog/details/6019*
[23] *http://zakon.rada.gov.ua/laws/show/z0313-07*

Table 2.8. Corn stover storage costs at the main storage facility

Indicators	Shredded corn stover	Large square bales	Round bales
Land rent and ground preparation costs of 1 ha, EUR/(ha·year)		400	
Cost of agrofibre and other materials for one stack, EUR/(stack·year)	273	427	427
Area for a double stack into account the fire protection rules, ha	0.31	0.44	0.48
Mass of corn stover in a double stack, t d.m.	160	1103	484
Dry matter loss[24], %	9		
Corn stover storage costs, EUR/t d.m.	2.7	0.6	1.4
Loading/unloading costs, EUR/t d.m.	4.2	2.5	3.6
Total storage costs at the main storage facility, EUR/t d.m.	**6.9**	**3.1**	**5.0**

Storage of large square bales under tarp costs 3.1 EUR/ t d.m., which is lower than that for round bales (5.0 EUR/t d.m.) and shredded corn stover (6.9 EUR/t d.m.).

[24] *https://store.extension.iastate.edu/product/14078*

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.

In Ukraine, there are no national standards for briquettes from corn stover, but briquettes producers can develop TUs (specifications) if they need them. For the standardization of briquettes from non-woody biomass, the International Organization for Standardization (ISO) adopted ISO 17225-7 "Solid biofuels – Fuel specifications and classes – Part 7: Graded non-woody briquettes" in 2014.

Specific information about biomass briquettes production is in ***UABIO's Position Paper №20*** "Analysis of possibilities for the production and use of agribiomass briquettes in Ukraine".

At present, corn stover briquettes aren't proposed in the Ukrainian market. But, current propositions for straw briquettes are from 80 to 90 EUR/t with VAT, and for wood briquettes the price is from 90 to 150 EUR/t with VAT. The estimated price for corn stover briquettes is 90 EUR/t with VAT because their fuel characteristics are better than straw briquettes.

Three levels of briquetting productivity have been chosen for the feasibility study:

1) **0.5 t/h** on the basis of the briquetting line PE "Briquetting technologies" (Ukraine) with the productivity of 500-600 kg/h[25] (a shredder ITS 1, an aerodynamic dryer SAD-0.6-1.2 and a briquetting press PBU-070-800M);

2) **2 t/h** completed with equipment of different Ukrainian manufactures, including 2 briquetting presses PBU-090-900M and a drum dryer;

3) **4 t/h** completed with **German and Ukrainian equipment** (5 briquetting presses RUF R6 and a drum dryer).

Basic input data for the techno-economic assessment of the production of briquettes from corn residues are:

- initial year the briquetting line produces 50% of the annual briquettes quantity;
- purchase of a used telehandler for bales loading operations;
- use of the existing building and electricity line;
- 2 persons of administrative staff for briquette productivity of 2 and 4 t/h;
- corn stover is in the large square bales with a price of 40 EUR/t d.m. with VAT;
- the main storage facility is situated close to the briquetting plant;
- corn stover bales storage costs 3.1 EUR/t d.m.;
- the selling price for corn stover briquettes is 90.0 EUR/t d.m. with VAT.

The operating costs for the three levels of briquetting productivity are given in Fig. 3.1. The main current expenditures for briquettes production from corn residues are feedstock costs (46-52%), electricity (12-13%), amortization (9-13%), and the labor costs (17% for the productivity 0.5 t/hour).

[25] *https://www.youtube.com/watch?v=twM_nmZ7esg&t=4s*

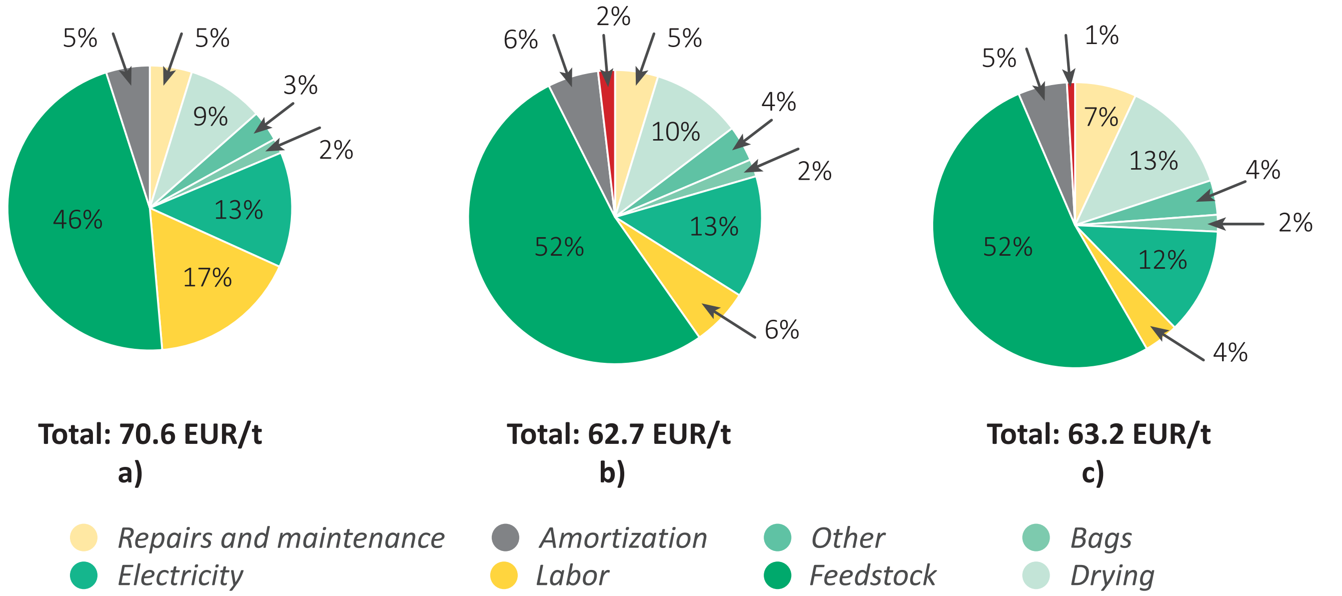

Fig. 3.1. The share of different operating costs for three values of briquetting productivity: a) 0.5 t/h; b) 2.0 t/h; c) 4.0 t/h.

The net costs of briquettes are 62.7 EUR/t for the productivity of 2 t/h, 63.2 EUR/t for 4 t/h, and 70.6 EUR/t for 0.5 t/h. Results of the feasibility study on corn stover briquettes production are given in Table 3.1.

Table 3.1. Techno-economic assessment of corn stover briquetting

Indicators	Productivity of briquetting line, t/h		
	0.5	**2.0**	**4.0****
Annual briquettes production, yr	**3000**	**12000**	**24000**
Capital costs, thous. EUR	147.5	598.8	1572.0
Operating costs, thous. EUR/y	193.4	677.5	1319.5
Loan (the share of equipment costs), %	70		
Loan rate, %	7		
Term of loan, y	5		
Corn stover bales costs on the plant, EUR/t d.m. without VAT	36.4		
Net cost of briquettes, EUR/t	**70.6**	**62.7**	**63.2**
Selling price for corn stover briquettes, EUR/t with VAT	90		
Annual revenue from selling of briquettes, thous. EUR	270.0	1080.0	2160.0
NPV, thous. EUR	39.2	677.9	1214.1
Simple payback period, yr	**6.0**	**3.7**	**4.4**
Discounted payback period (under discount rate of 7%), yr	7.8	4.2	5.2
IRR, %	**13.9**	**34.7**	**26.1**

** Initial year the briquetting line produces 50% of the annual briquettes quantity.*
*** The line with productivity of 4 t/h is equipped with German briquetting presses.*

Given the initial data and assumptions, the net present value of the project with foreign briquetting presses with the productivity of 4 t/h is about 1214 thous. EUR with an internal rate of return of 26.1%. The simple payback period is 4.4 years, and the discounted payback period is 5.2 years. The economic indicators for the project with the productivity of 2 t/h, based on Ukrainian equipment, is even better, IRR is 34.7%, and the simple payback period is 4.2 years.

The selling price of briquettes, the productivity of the briquetting equipment, as well as the price of the feedstock for briquettes production, have the most significant influence on the basic economic indicators (Fig. 3.2). For the productivity of 4 t/h, if the selling price of corn stover briquettes is decreased by 10% (81 EUR/t with VAT), IRR will be 11.1%. But, if the selling price of corn stover briquettes increases by 10% (99 EUR/t with VAT), IRR will be 40.8%.

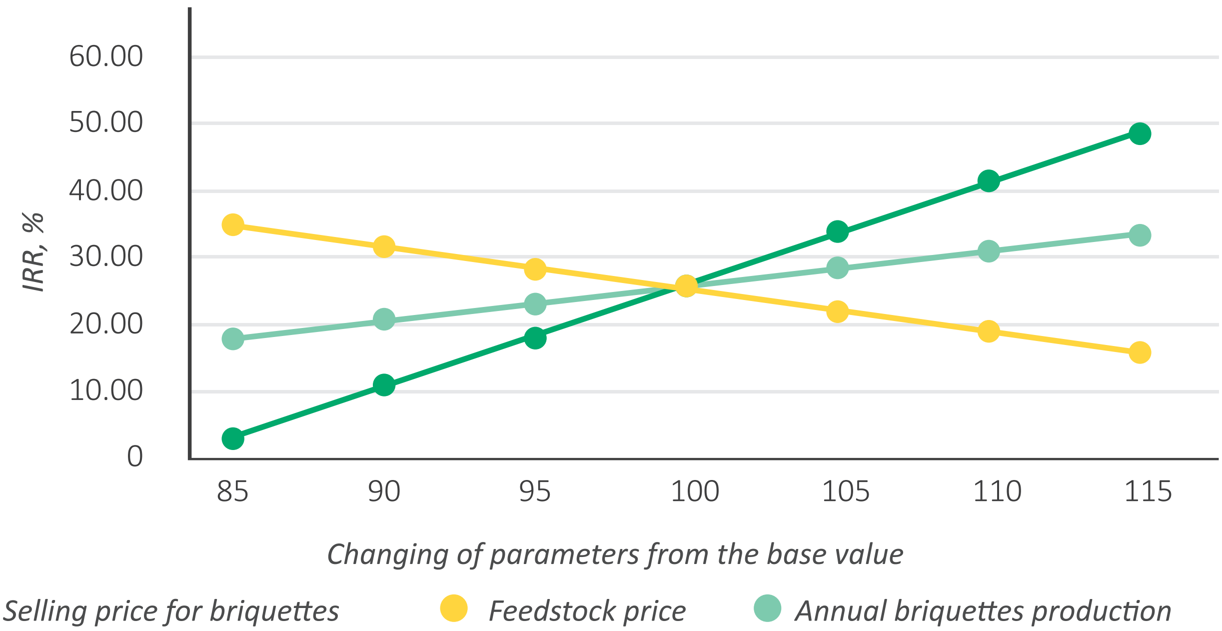

Fig. 3.2. Dependence of IRR from the change of selected parameters

4 FEASIBILITY STUDY ON PELLETS PRODUCTION FROM CORN RESIDUES

Agricultural biomass is pelletized in order to increase the efficiency of logistic operations and expand the possibility of its energy use. Pellets from corn residues are referred to non-woody pellets, and the technology 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, have a shape of cylinders with diameter < 25 mm, random length (typically 3.15 mm to 40 mm), with broken ends, obtained by mechanical compression[26].

The main characteristics that affect the organization of the production process of granulation are the initial condition of the biomass (particles size,

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

initial volume reduction, presence of inclusions), as well as the 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 without intermediate drying. More information about pellets from agrobiomass is in the ***report "Comprehensive analysis of the Ukrainian biomass pellets market (definition of growth points)"*** that was prepared by the experts of SEC "Biomass" within the UNDP project "Development and commercialization of bioenergy technologies in the municipal sector of Ukraine".

For the widespread international trade of solid biofuels, international standards to facilitate buying and selling biomass fuels, including pellets from non-woody biomass, have been created, which are gradually harmonizing in Ukraine. The national standard DSTU EN 15234-6:2017 "Solid biofuels – Fuel quality assurance – Part 6: Non-woody pellets for nonindustrial use" was harmonized with European normative documents EN 15234-6:2012 and came into force from October 1, 2017. The quality requirements for non-woody pellets as the product is set by the international standard ISO 17225-6:2014 "Solid biofuels - Fuel specifications and classes - Part 6: Graded non-woody pellets", which has been not harmonized in Ukraine yet. However, some pellet producers develop TUs for pellets from corn stover. The certification of the pellets lets the producers possibility to sell their product at higher price. In this case, the pellet consumer can buy pellets of guaranteed quality.

Proposals for pellets from corn stover are very limited on the Ukrainian market. But, current propositions for straw pellets are from 80 to 95 EUR/t with VAT, and for wood pellets they are from 95 to 160 EUR/t with VAT. The estimated price for corn stover pellets is 90 EUR/t with VAT because their fuel characteristics are better than straw pellets.

Three levels of pelleting productivity were chosen for the feasibility study:

1) **2.0 t/h** on the basis of the pelleting line BIOsmartex with the productivity of 1500-2500 kg/h, completed with Ukrainian equipment, including the drum drier for biomass;

2) **4.0 t/h** based on import and Ukrainian equipment;

3) **10.0 t/h** based on import and Ukrainian equipment.

Basic input data for techno-economic assessment of the pellets production from corn residues are:

- pelleting line produces 50% of annual volume of pellets during the first operation year;
- use of the existing building and electricity line;
- 2 persons of administrative staff;
- corn stover is in large square bales with a price of 40 EUR/t d.m. with VAT;
- main storage facility is situated close to the pellet plant;
- corn stover bales storage costs 3.1 EUR/t d.m.;
- selling price for corn stover pellets is 90.0 EUR/t with VAT.

The operating costs for the three levels of pelletizing productivity are given in Fig. 4.1. The main current expenditures for the pellets production from corn residues are feedstock costs (47-52%), electricity (14-19%), and amortization (9-11%). The net costs of pellets are 64.1 EUR/t for the productivity of 10 t/h, 67.3 EUR/t for 4 t/h, and 70.5 EUR/t for 2 t/h.

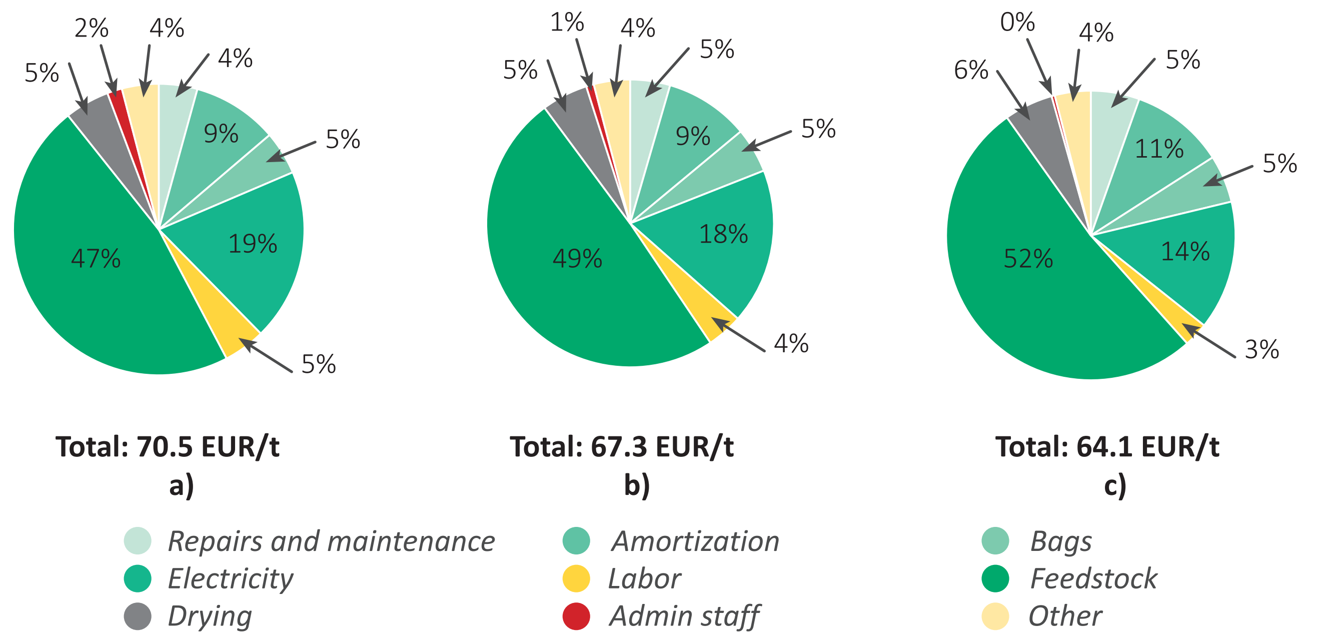

Fig. 4.1. The share of different operating costs for three values of pelletizing productivity: a) 2 t/h; b) 4 t/h; c) 10 t/h.

Results of feasibility study on corn stover pellets production are given in Table 4.1. Given the initial data and assumptions, the net present value of the largest project (10 t/h) is about 2899 thous. EUR with the internal rate of return of 29.1%. The simple payback period is 4.1 years, and the discounted payback period is 4.8 years.

Table 4.1. Techno-economic assessment of corn stover pelletizing

Indicators	**Productivity of pelletizing line, t/h**		
	2.0	**4.0**	**10.0**
Annual pellets production, yr	**12000**	**24000**	**60000**
Capital costs, thous. EUR	642.0	1223.5	3228.4
Operating costs, thous. EUR/y	766.1	1461.5	3920.9
Loan (the share of equipment costs), %	70		
Loan rate, %	7		
Term of loan, y	5		
Corn stover bales costs on the plant, EUR/t d.m. without VAT	36.4		
Net cost of pellets, EUR/t	**70.5**	**67.3**	**64.1**
Selling price for corn stover pellets, EUR/t with VAT	90.0		
Annual revenue from selling of pellets, thous. EUR	1080.0	2160.0	5400.0
NPV, thous. EUR	168.5	765.3	2899.2
Simple payback period, yr	**6.0**	**4.8**	**4.1**
Discounted payback period (under discount rate of 7%), yr	7.8	5.7	4.8
IRR, %	**13.8**	**22.6**	**29.1**

** Initial year the pelleting line produces 50% of the annual pellets quantity*

The selling price of pellets, the productivity of the pelleting equipment, as well as the price of the feedstock for the pellets production, have the greatest influence on the basic economic indicators (Fig. 4.2). If the selling price of corn stover pellets is decreased by 10% for the productivity of 10 t/h (81 EUR/t with VAT), IRR will be 10.9%. But, if the selling price of corn stover pellets is increased by 10% (99 EUR/t with VAT), IRR will be 47.2%.

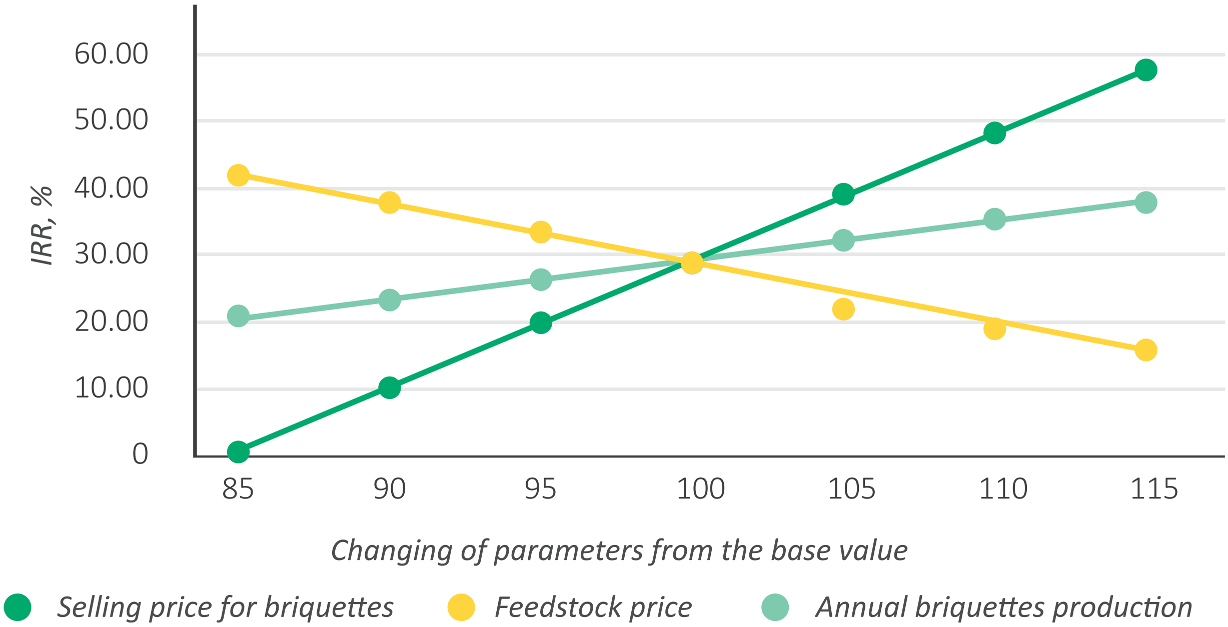

Fig. 4.2. Dependence of IRR on the change of some selected parameters

CONCLUSIONS

1. General tendency is growth of corn yield in Ukraine. In 2018, 35.8 Mt of grain corn with the average yield of 78.4 centners/ha were harvested, the highest on record. In addition to grain corn, the huge amount of corn residues (stalks, leaves, cobs, wrap of ear, etc.) are formed; they can be used for briquettes and pellets production.

2. In 2018, the economic potential of the corn residues for energy in Ukraine was 18.6 Mt or 3.6 Mtoe. The leading regions were Poltava oblast (with the economic potential of corn residues of 489.6 ktoe), Chernihiv oblast (382.2 ktoe), and Vinnytsia oblast (372.2 ktoe).

3. Techno-economic assessment of four corn residues supply chains has been performed for large square bales, round bales, and shredded corn stover on the basis of a forage harvester and a forage wagon. The most effective supply chain is the corn residues harvesting in the large square bales (**simple payback period is 4.8 years, IRR is 22.5%** for the scenario of harvesting of 3.5 t d.m./ha and selling price of corn stover bales of 40 EUR/t d.m. with VAT). For the transportation distance less than 20 km, a forage loader wagon can also be feasibly used.

4. Storage of large square bales under tarp costs 3.1 EUR/t d.m., which is lower than that for round bales (5.0 EUR/t d.m.) and shredded corn stovers (6.9 EUR/t d.m.).

5. In the case of corn residues briquettes and pellets selling at the price of 90 EUR/t with VAT for the briquetting productivity of 2.0 t/hour, **the simple payback period is 3.7 years, IRR is 34.7%.** For the pellets production with the productivity of 10.0 t/hour, **the simple payback period is 4.1 years, IRR is 29.1%.**

Thus, **the production of pellets and briquettes from corn residues is an economically feasible activity.**

ABBREVIATIONS

d.m.	dry matter
DSTU	State Standard of Ukraine
EBRD	European Bank for Reconstruction and Development
HHV	higher heating value
IRR	internal rate of return
kt	1000 t
m.c.	metric centner
Mt	million tons
MY	marketing year
NAAS	National Academy of Agrarian Sciences
NPV	net present value
SC	supply chain
SSSU	State Statistics Service of Ukraine
TU	technical specification
UABIO	Bioenergy Association of Ukraine
UNDP	United Nations Development Programme
USDA	United States Department of Agriculture
VAT	value-added tax
W	moisture content

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