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AGRICULTURAL RESIDUES FOR ENERGY. WHAT YOU SHOULD KNOW ABOUT ORGANIZATIONAL AND TECHNICAL SOLUTIONS

The present position paper #24 of the Bioenergy Association of Ukraine belongs to the planned series of publications on the main issues of bioenergy development in Ukraine. The note addresses issues related to peculiarities of agrarian waste utilization for further production of heat and electricity. There is an analysis of world experience and examples of successful projects, including Ukraine. The fuel characteristics of agricultural waste and the features of their energy use are considered. The main attention is paid to organizational, technical and environmental issues, as well as recommendations for the effective implementation of projects in Ukraine.

Prepared practical recommendations can be useful both in the development of policy decisions and in the preparation and implementation of investment projects

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Terms and definitions

The key terms and definitions used in this position paper are given in accordance with DSTU EN 14588: 2013 “Solid biofuels. Terms and definitions (EN 14588: 2010, IDT)".

agrofuels: Biofuel obtained from crops and/or agricultural waste used as an energy source.

biofuel: Fuel obtained from biomass directly or through intermediate stages.

solid biofuel: A solid fuel that is produced from biomass directly or indirectly.

biomass: Material of biological origin, except for materials that occur in geological formations and turned into fossil remains.

fruit biomass: Biomass obtained from parts of plants that contain seeds.

herbaceous biomass: Biomass obtained from plants that do not have a tree-like trunk but a stem and that die at the end of the growing season.

herbaceous fuels: All types of biofuels obtained from herbaceous biomass.

agricultural residues: Biomass waste from agricultural production, logging and primary processing in rural areas.

horticultural residues: Biomass waste generated during the production, collection and processing of fruit plants in gardening, including hothouses.

baled biofuel, bale: Biofuel that has been compressed and compacted to give shape and compactness.

bundled biofuel, bundle: The connection of units of solid biofuel with the longitudinal orientation of the particles of material in it.

ash content: The mass of inorganic residue formed after fuel combustion under standard conditions. It is usually expressed as a percentage by weight related to dry matter.

ash fusibility; ash melting behavior: The property of ash during heating under standard conditions to gradually turn from solid to liquid through the stages of sintering, softening and melting.

net calorific value: The amount of heat equal to the higher calorific value less the heat of vaporization of water released during the combustion of coal (at 0.1 MPa).

volatile matter: Loss of fuel mass, adjusted for moisture, during heating without access of air at high temperatures under standard conditions.

1. Introduction and analysis of problems

At present, agricultural waste and agrobiofuels are not widely used in energy, and their share in the energy balances of the world is insignificant. At the same time, the potential for use is quite high, especially in agricultural countries such as Ukraine.

The development of new, efficient technologies and the availability of new equipment creates the preconditions for the widespread use of agricultural waste in the future. The availability of a limited amount of fossil fuels and further national plans for the development of renewable energy and the reduction of greenhouse gas emissions requires the involvement of new kinds of raw materials and fuels for energy production.

The limited potential for increasing wood biofuels use and the much higher potential of agricultural waste opens up new development opportunities for the energy sector and agriculture. Analysis of the biomass consumption structure indicates the need for greater use of agricultural waste and special energy crops as fuel.

Agricultural waste is the ideal source of energy. Raw materials do not need to be grown separately - this is a by-product of agriculture.

In addition to political, financial and economic barriers, the widespread development of the energy use of agricultural waste is hampered by a number of significant constraints imposed by organizational and technological solutions, environmental requirements and a lack of extensive practical experience. The presence on the market of a limited number of manufacturers of technological equipment and its high cost hinder the transition to the use of agricultural waste in both the energy sector and the district heating sector.

Previous UABIO position papers[1] have already been devoted to overcoming barriers in the organization of the “procurement-supply” chain, development of the biofuel market, production of biofuels from agrowaste and other issues. The world experience of the use of agricultural waste and residues is studied, organizational and technical issues of energy production are analyzed in this position paper. Prepared practical recommendations can be useful both in the development of policy decisions and in the preparation and implementation of real investment projects.

The slowdown in economic development in the world and the rapid decline in the price of traditional energy resources directly affect the development of bioenergy and reduce interest in the implementation of new bioenergy projects. At the same time, both the recovery of high prices for traditional energy sources and the growth of investment in the renewable energy sector, where bioenergy continues to occupy a leading position, are expected in the short and long term. Ukraine has its own renewable resources, national aims and a goal where energy should become "green".

[1] https://uabio.org/materials/uabio-analytics/

2. World experience in the use of agricultural waste for energy purposes

The world experience of energy use of agricultural waste and agrobiofuels is not so great compared to the use of wood biofuels. At the same time, technologies have already reached a commercial level, and some countries have been successfully developing this area for many years. However, most countries are only at the beginning of this path, like Ukraine. This review of world experience will contribute to a broader understanding of the existing practice of agricultural waste used in the world and the new opportunities that open up for Ukraine.

Denmark

Denmark is a world leader in renewable energy. Historically, Denmark has a low level of forest cover, which has given impetus to the rapid development of agricultural waste use. A decentralized approach to heat supply, high taxes on fossil fuels and imported energy resources have contributed to the development of renewable energy in Denmark. The ban on the open burning of straw in the fields was a significant factor that contributed to the reorientation and rapid development of energy use of straw.

The Danish Institute of Technology was involved in long-term energy planning in the country. The directions of further development were determined based on development scenarios, forecasts of production and consumption of energy and fuel, fuel prices and tax policy. These directions also based on the use of local renewable resources, including agricultural waste. Long-term planning and government support have contributed to the creation of engineering companies and factories for the production of new specialized equipment. Decentralization in the field of heat supply has contributed to the creation of a large number of energy cooperatives, co-owners of which were both fuel suppliers and consumers of heat energy. Cooperatives independently determined the level of tariffs for thermal energy, fuel purchase prices, and the level of other operating expenses.

Denmark is a demonstration site with leading manufacturers of agricultural waste equipment, as well as a large number of facilities with a variety of technological solutions and parameters, which will be described in the following chapters of the position paper.

About 1.6 million tons (28%) of straw is burned for energy production[2] , and only 41% remains in the field as fertilizer. In Denmark, there are more than 10,000 farm straw-fired boilers (0.1-1.0 MW) and about 55 boiler houses in the district heating system (0.5-12 MW). In addition, CHPs use wood chips, solid waste or fossil fuels together with straw. All power plants operate in a cogeneration regime with high efficiency, which allows providing low cost of heat and electricity.

United Kingdom

Bioenergy in the UK has begun to develop rapidly in recent decades, and now more than 80 biomass power plants with a total capacity of more than 4,000 MW operates. Another 20 facilities (800 MW) and a small number of farm straw boilers are in various stages of preparation for construction. The majority of TPPs and CHPs are privately owned, have a capacity of up to 50 MW and run on wood biomass, poultry litter, miscanthus and straw. Due to increasing environmental requirements for coal-fired power plants, some of them have been converted to co-firing of biomass with coal, and some are closed and completely converted only for biomass combustion (Drax, RWE, E.ON, DONG Energy, etc.).

[2] Experience with straw firing in Danish combined heat and power plants

Melton Renewable Energy UK Limited is one of the leading independent producers of renewable energy in the United Kingdom. The total installed capacity of the facilities is 165 MW, of which 111 MW – five biomass power plants. In 2000, the company was the first in the UK to build the CHP Ely Power Station[3], which runs on cereal straw, rapeseed and miscanthus. The installed electric capacity of the station is 38 MW, and the annual consumption of straw is 200 thousand tons.

In December 2011, the specialized investment fund Glennmont Partners decided to finance the construction of the CHP Sleaford Renewable Energy Plant[4] on straw with a capacity of 38 MW and 168 million pounds cost. The overall management of the plant was carried out by Natural Power. Eco2 specialists managed the fuel supply, and BWSC was responsible for equipment supply, operation and maintenance. The power plant started operating in 2014. The station employs 30 people, and another 50 people are involved in the supply of fuel. Annually, the plant burns 240,000 tons of straw (approximately 55 bales per hour), which is supplied from farms within a radius of 50 kilometers. Excess heat at the CHP is supplied free of charge and used for heating of the public swimming pool, bowling alley, football center, primary school and the district council office.

Two more straw power plants were built using similar technology from the Danish company BWSC. The first CHP Brigg Renewable Energy Plant[5] with 40 MW capacity started operating in January 2016, and the second Snetterton Renewable Energy Plant[6] with 44 MW capacity started operating in September 2017. The construction period of both stations was about 2.5 years. The project was developed by BWSC East Anglia (BEAL), which brought together a partnership of key renewable energy experts to design, build and manage the project. The joint ventures are owned by the Scandinavian contractor Burmeister & Wain (A/S BWSC) and the Danish Infrastructure Fund (K/S Copenhagen Infrastructure Partners). Contract with BWSC is for construction and operation. The main fuel supplier, the Worldwide Farming Partnership, is committed to supplying at least 50,000 tons of straw, which is about 20% of total needs. The rest of the fuel is purchased from local farms.

Spain

The group of companies ACCIONA[7], which works exclusively in the field of renewable energy, works in more than 20 countries on five continents. The company operates with five technologies: wind, solar photovoltaics, hydroelectric, biomass and solar thermal. The company has three operational straw power plants with a total capacity of 61 MW.

The Sangüesa power plant (30 MW) was the first in Spain (commissioned in 2002). The station consumes 160 thousand tons of straw per year, which is supplied by local farmers from an area within 75 km radius. Ash from straw burning is used for organic fertilizer production.

The Bivriesca CHP (16 MW) worth €40 million was built in 2010. CHP is located in an agricultural region and has a large amount of agricultural waste. Seventeen specialized companies supply 102 thousand tons of straw per year (based on long-term contracts). The implementation of this power plant has led to the creation of 100 permanent new jobs. A similar MIAJADAS power plant (15 MW) was built in 2010. It works on vegetable waste and allows the use of corn and wood waste.

[3] https://www.mreuk.com/ely-power-station
[4] http://www.sleafordrep.co.uk/?page_id=817
[5] https://www.briggbiomass.com/
[6] https://www.snettertonbiomass.com/
[7] https://www.acciona-energia.com/areas-of-activity/other-technologies/biomass/

Germany

In Germany, about 30 million tons of straw are produced, of which 8-13 million tons can be used for energy purposes. Although straw is one of the most important agricultural wastes, it is not widely used for energy purposes[8]. As of 2007, there were about 130 straw-fired installations in the country. Combustion emissions significantly constrain the development of straw use in Germany, and therefore other technologies are considered as alternatives - straw fermentation and production of liquid biofuels. The biggest driving forces in the development of bioenergy are the national goals for the production of heat and electricity from renewable sources and preferential taxation of certain fuels, including biomass of agricultural origin.

Bioenergiekraftwerk Emsland GmbH & Co. KG[9] (Emlichheim city) has been operating a straw power plant with a capacity of 11.5 MW since 2013. The annual consumption of straw is about 75 thousand tons, which is 15-20 trucks per day. Straw should be free of impurities and have up to 22% of moisture. The price of straw in 2016, on average, was 80 euros/ton. The operation of the power plant on straw avoids getting into the atmosphere up to 100 thousand tons of CO_{2e} pollutants. The combined production of electricity and heat allows achieving the efficiency of up to 90%. The produced heat is supplied to a local heating network with a length of about 30 km. Consumers of thermal energy in the form of steam and hot water are a potato starch factory, public facilities, a hospital, individual and apartment buildings.

Czech Republic

Private company EC Kutná Hora s.r.o.[10] operates its own CHP on grass biomass and provides heat supply services. The electric capacity of the CHP is 23 MW. The source of energy is grain and rapeseed straw and purposefully grown energy crops. The annual consumption of straw is 55 thousand tons. As a rule, the supply of raw materials is carried out at a distance of up to 50 km from the power plant. The company has a long-term contract for 10 years and provides straw harvesting services for its partners. The company offers for fuel suppliers the opportunity to take a certified ash-based fertilizer after combustion.

A private company Mostek energo s.r.o.[11] was created in September 2011 and included RSJ Investments (92%) and Dewarec (8%), which provided the project with the necessary financial resources. The project lasted from 2011 to 2015. The total investment costs for the project amounted to 525 million Czech crowns. With very few exceptions, the complete technology was manufactured in the Czech Republic and supplied by Czech partners. The power plant is equipped with a steam boiler with a fluidized bed, suitable for burning a wide range of different types of biomass. The electric capacity of the CHP is 4.9 MW in the condensing regime. Condensing heat from condensing cooling is partially used for air conditioning of raw material storage.

TTS energo s.r.o. [12] in Třebíč is the operator of three large biomass boiler houses that supply thermal energy to district heating networks. During the period 2001-2004, water heating and thermal oil boilers on wood, as well as a cogeneration unit with an ORC module, were installed at the Třebíč - Sever boiler house. A water-heating straw-burning boiler with a capacity of 5 MW was put into operation in 2006. Another Třebíč-Jih boiler house has two 3 MW wood-fired boilers on wood chips and two 5 MW hot-water boilers running on straw and using its own cigar burning technology.

[8] Impact of promotion mechanisms for advanced and low-iLUC biofuels on markets: Straw for bioenergy.
[9] http://www.bioenergie-emsland.de/
[10] https://www.eckh.cz/cze/index.html
[11] https://www.mostekenergo.cz/
[12] https://www.ttsenergo.cz/

Poland

According to various estimates, the volume of straw production in Poland is from 12 to 30 million tons, of which the excess is 7-12 million tons with 3.5 t/ha average straw yield. By 2012, about 6 million tons of straw were used for energy production in high-capacity installations and 1.5 million tons in small units.

There are about 100 low-capacity boilers (~100 kW) on straw and more than 40 small and medium-sized boilers in the district heating system (0.5-7 MW) in Poland. In addition, DP CleanTech and Polish Energy Partners (PER) built a 30 MW straw TPP (Winsko)[13]. The annual demand for straw is 220-240 thousand tons. Reserve fuel for TPP is wood chips.

The district heating company PEC Lubań[14] operates a combined hot water boiler with 1 MW, 2x3.5 MW boilers using baled straw. The company independently harvests straw and keeps a stock in the amount of 1 thousand tons on the territory of the boiler house in a closed warehouse. Straw in the field is bought at a price of 80 zlotys per ton. The project was implemented with the support of EcoFound in the form of a subsidy (43%), a loan from the Provincial Fund for Environmental Protection (20%), and own funds (37%). About 32% of heat energy is produced from straw and supplied to heat networks, covering the needs of 60% of consumers in the city with a population of 24 thousand people. The use of straw as a fuel has reduced the use of coal and reduced emissions of pollutants into the atmosphere.

HOST has implemented several projects of straw boilers. In 2009, a straw-burning boiler house with a 2.5 MW water boiler was put into operation in Radzikow. From 1,600 tons of straw, about 5,000 MWh of thermal energy is produced annually to provide central heating of the surrounding offices and premises. In 2008, a boiler house with boilers with a capacity of 1.5 MW and 2x0.5 MW on straw briquettes was built in Poddebice, which supplies thermal energy to the city's central heating network.

GDF Suez is the owner and operator of the Polaniec biomass power plant[15], which was built in 2012 on the site of an existing coal-fired power plant. The plant can use 80% of wood chips and 20% of agricultural waste as fuel. The capacity of the biomass power unit is 205 MW. It has a boiler with a circulating fluidized bed (CFB Foster Wheeler), which is able to work exclusively on biomass and with the addition of coal. The power plant was built to complement the European Union's goal of generating 15% of energy from renewable sources by 2020. Unfortunately, after the abolition of state support for the production of "green" electricity in 2012, the consumption of straw pellets and the dynamics of implementation of new projects stopped. Straw prices fell from 125 euros to 25 euros per tonne.

Hungary

In 2007, Veolia Energy Hungary[16]acquired control of all Pannonpower companies operating in Hungary. As a result of fuel changes since 2013, power plants use wood chips, straw of cereals, energy crops, and corn waste.

The subsidiary Pannon-Hő Kft was founded by the group in 2005 to implement and operate the 35 MW Pécs Power Plant, which uses herbaceous agricultural products (straw, miscanthus). Pannon-Biomassza Energetikai's own subsidiary was established to provide commercial and logistical support. The main task of the company is to supply biomass, purchase and storage of materials and parts necessary for work, as well as the sale of ash. Given the proximity to the border with Croatia,

[13] https://polenergia.pl/pol/sites/default/files/press/120316_prezentacja_winsko.pdf
[14] http://www.pecluban.pl/
[15] http://www.pecluban.pl/
[16] http://biomassza.veolia.hu/dokumentumok/szalma

the company, including outside the country, purchases agricultural waste, in particular, such types of agrobiomass as cereal straw (wheat, rye, barley, oats, triticale), soybean, reed, etc.

China

Straw energy production technologies are also actively developing in China. DP CleanTech[17] introduced 34 straw power plants with a total capacity of 1,200 MW in the country in 2006-2012. A typical example is a 30 MW TPP (160,000 tons of straw per year) in Liaoyuan, which supplies 200 GWh of electricity to the national grid.

In countries such as India, Pakistan, Malaysia, Slovakia, France, Bulgaria, Ukraine and others, there are some single examples of farm, industrial or energy facilities that use agricultural waste as fuel, and this energy sector is just beginning to develop. Unfortunately, information on the industrial energy use of sunflower stalks, corn and other crops inherent in Ukraine has not been found. Lack of practical experience may be due to a lack of sufficient energy potential in EU countries or a lack of industrial procurement practices/equipment that do not allow for the required level of industrial consumption to fully supply TPPs/CHPs.

Analysis of world experience shows that the implemented projects have been successful due to the use of proven technologies and equipment, the use of thermal energy, a high level of energy efficiency. Balanced public policy and close cooperation with agricultural enterprises, relevant associations and local governments were the basis for mutually beneficial long-term development. It is private companies that own power plants that operate CHPs and are suppliers of heat and electricity. In order to increase the reliability of construction projects and operational activities, companies engage EPC/EPCO contractors and establish their own subsidiaries responsible for fuel supply.

World experience once again confirms the possibility of using agricultural waste to meet energy needs.

[17] https://www.dpcleantech.com/

3. Energy potential of plant waste from agriculture

The analysis of the world experience of energy use of agricultural waste and the practice of energy projects are directly related to the available raw materials and energy potential of waste. Arable land, yield, climatic conditions, market conditions, public policy are the main factors influencing agricultural practices in a particular region and determine the amount of resources available for energy use (**Table 1**).

Table 1 - Sown area in some EU countries and Ukraine in 2018, thousand hectares[18]

	Barley	Maize	Oat	Rape	Rye	Sunflower	Wheat	Wheat/ sunflower	Wheat/ maize
Bulgaria	104	445	11	183	8	789	1 212	1.54	2.73
UK	1 138	-	171	583	32	-	1 748		
Greece	129	113	80	9	10	80	404	5.07	3.57
Denmark	795	6	83	143	93	-	426		67.27
Estonia	138	-	40	73	11	-	155		
Spain	2 569	322	557	78	136	691	2 064	2.99	6.4
Italy	262	591	107	14	4	104	1 822	17.54	3.08
Latvia	118	-	87	120	22	-	417		
Lithuania	226	13	103	205	21	-	773		57.7
Netherlands	36	9	1	2	2	-	112		11.85
Germany	1 622	411	140	1 224	523	20	3 036	155.71	7.39
Poland	976	645	497	836	894	6	2 417	426.69	3.75
Romania	422	2 443	161	633	10	1 006	2 112	2.1	0.86
Serbia	106	902	26	46	5	239	643	2.69	0.71
Slovakia	124	179	13	154	12	69	403	5.86	2.25
Hungary	244	944	23	331	26	619	1 030	1.66	1.09
Ukraine	**2 484**	**4 564**	**196**	**1 039**	**148**	**6 167**	**6 620**	**1.07**	**1.45**
France	1 768	1 422	92	1 616	24	553	5 232	9.47	3.68
Croatia	51	235	16	55	1	37	138	3.73	0.59
Czech Republic	325	82	43	412	25	20	820	40.57	10.01

As can be seen from the table, some EU countries do not grow corn and sunflower, and therefore residues in the form of straw from cereals remain the main agricultural waste. The significant potential of rapeseed waste is concentrated in Germany, Ukraine, France and Poland. Large sown areas under corn are in Romania, France, Ukraine, and under sunflower - in Ukraine, Romania, Bulgaria. The ratio of sown areas under wheat to sunflower and corn in the EU and Ukraine is important, which only confirms the priority in the use of grain straw over other agricultural waste in the EU.

It is estimated that special energy crops are grown on about 5.5 million hectares of agricultural land. This is 3.2% of the total crop area in the EU27. The main share of land is used for growing oilseeds for biodiesel production - 82%, ethanol production - 11%, biogas - 7%, and only about 1% is used for growing perennials for solid biofuel production[19]. Thus, EU public policy was aimed at achieving the required level of production of

[18] http://www.fao.org/faostat/ru/#data
[19] Atlas of EU biomass potentials Deliverable 3.3.

first-generation motor fuel and biogas. The transition to the production of second-generation liquid biofuels from lignocellulose raw materials will lead to an increase in the consumption of crop residues.

Methodology for assessing the potential of straw, etc. agrowaste for bioenergy was developed by the JRC in 2006 and is based on the use of agri-waste volumes that ensure a stable yield and maintain a constant level of carbon in the soil. It is accepted that 40% of the potential of cereal residues (wheat, rye, oats, and barley) and 50% of other crops can be used for energy purposes. The potential of cereal straw is well distributed in almost all EU countries, but countries such as France, Germany, Poland, Italy, Hungary and the United Kingdom have the greatest potential. The concentration of straw formation in Denmark is the highest, although the potential remains limited compared to most EU countries.

In Ukraine, the energy potential of biomass available for energy production is almost 23 Mtoe/year (**Table 2**), and the available potential of raw materials and market availability is one of the important prerequisites for the successful development of bioenergy.

The main components of the energy potential of biomass are waste and by-products of agriculture or agricultural residues (10.1 Mtoe/year or 44% of the total potential) and energy crops (7.5 Mtoe/ year, 32%). The largest share of the potential of agricultural waste is accounted for by-products and wastes from the production of grain maize, or maize (35%), and straw from cereals (33%).

The contribution of wood biomass to the energy potential of biomass in Ukraine is relatively small and amounts to about 3.1 Mtoe/year or 13% of the total potential. The other components of the energy potential of biomass in Ukraine, which together account for about 10%, are liquid biofuels (biodiesel, bioethanol) and biogas obtained from various raw materials (waste and by-products of agriculture, industrial and municipal wastewater, solid waste).

Table 2 - Energy potential of biomass in Ukraine (2018)

Biomass type	Theoretical potential, Mt	The potential that is available for energy	
		Part of the theoretical potential, %	Mtoe
Straw of cereals	32.8	30	3.36
Rapeseed straw	4.9	40	0.68
By-products of corn production on grain (stalks, cores)	46.5	40	3.56
By-products of sunflower production (stems, baskets)	26.9	40	1.54
Secondary agricultural waste (sunflower husk)	2.4	100	1.00
Wood biomass	17.6	-	3.08
Liquid motor biofuels	-	-	1.21
Biogas	3.2 billion m³ CH_4	-	1.05
Energy crops:			
- willow, poplar, miscanthus *	11.5	100	4.88
- corn (for biogas)*	3.0 billion m³ CH_4	100	2.57
Total	-	-	22.93

** Subject to the cultivation of 1 million hectares of unused agricultural land.*

The volume of agricultural biomass in Ukraine is increasing every year due to the general trend of growth of production and yield of major crops. Since 2000, the energy potential of cereal straw, by-products and waste from maize for grain and sunflower has tripled - from 2.76 Mtoe in 2000 to 8.46 Mtoe in 2018.

The situation with real consumption of biomass for energy and biofuel production in Ukraine is, in fact, the opposite of the potential structure. On average, the energy potential of biomass in Ukraine is used by 11%. Wood biomass is most actively used, and the use of the potential of waste and by-products of agricultural origin remains low. In Ukraine, for the energy purposes, only sunflower husk is used quite actively among agrobiomass - about 70% of its potential. The production of energy/biofuels from straw is at the level of 4% of the available potential. There are single examples of energy use of corn, including for the production of pellets and briquettes, while examples of energy production from sunflower stalks or baskets are currently unknown.

4. Characteristics of agricultural waste as a fuel

Agricultural waste can be good fuel but has specific characteristics that distinguish them from other types of biomass. These characteristics are related not only to their origin but also to their physicochemical properties.

According to the classification of solid biofuels (**Annex 1**), agricultural waste belongs to the group of the second level of grass biomass. This group includes cereals, oilseeds, grasses, roots and flowers, as well as grass biomass of gardens, parks, roadside plantations, vineyards and orchards, artificial mixtures. For a clear and correct understanding, the previous sections provide key terms and definitions according to the standards.

The most important physical characteristics of fuel are the following: density, size, water content, ash content, impurity content, etc. Important chemical characteristics include calorific value, chemical and elemental composition, composition and characteristics of ash, etc. Physical properties of fuel determine the characteristics of procurement, storage, transportation, fuel storage, and affect the choice of equipment for grinding, fuel supply and combustion technology. The chemical composition of the fuel determines the design of the equipment and its parameters that should ensure reliable and long-term operation. Successful selection of equipment will help to avoid slag and corrosion, minimize emissions of pollutants, and, most importantly, reduce maintenance costs.

The water content of some parts of corn is heterogeneous and decreases rapidly after 120 days from the date of sowing. Corn cobs are always wetter (W 35-45%) than grain (W 22-35%), but evaporate moisture more intensely during drying[20]. Immediately after harvesting, the humidity of the stems is in the range of 45-60%. Sunflowers are harvested in September-November. When harvesting the crop in the optimal phase of maturity, the water content of the baskets is 70-75%, stems - 60-70%[21]. Water content also strongly depends on the time of harvest and weather conditions, and therefore heavy rainfall during harvest can lead to the inexpediency of harvesting. It is necessary to harvest corn and sunflower waste in the period when the water content is less than 20%.

For energy purposes, agricultural waste is usually supplied in a convenient form for transportation and storage (pellets, briquettes or bundles and bales, the standard sizes of which are given in **Annex 2**). Standardized values of indicators, characterizing the properties of different types of grass biomass and agricultural waste, are given in **Annexes 3, 4**. Studies of the properties of individual fuel samples[22][23] confirm that the range of indicators can be very wide, and in each case, it is necessary to conduct laboratory studies of the fuel composition.

As for Ukraine, it is quite possible to assume that the content of chlorine and alkali metals in straw and corn stalks is lower than in the straw of European countries. This is due to a significant reduction in the

[20] Possibilities of harvesting corn by-products for grain for energy use in Ukraine. UABIO Analytical Note № 16
[21] Prospects for the use of agricultural waste for energy production in Ukraine. UABIO Analytical Note № 7
[22] Analysis of the possibilities of production and use of agrobiomass briquettes in Ukraine. UABIO Analytical Note № 20
[23] https://phyllis.nl/Browse/Standard/ECN-Phyllis

application of mineral fertilizers to crops over the past 20 years. **Table 3** shows comparative data of laboratory studies of Ukrainian and European samples, confirming the reduced content of sulfur, chlorine and potassium salts and the increased temperature of the onset of ash deformation in local fuel samples.

Table 3 - Comparative characteristics of fuel samples [24]

	Corn of Ukrainian origin		Average values according to the database			
	Cobs	Stalks	Corn stalks	Wheat straw	Pine chips	Sunflower stalks
Humidity, W_r, %	7.7	10.5	6.25	9.71	8.83	0
Ash, A_d, %	2.1	5.6	6.37	6.08	0.7	8.55
Volatiles, V_{daf}, %	85.3	81.9	81.31	81.37	84.26	-
Carbon, C_{daf}, %	49.08	50.04	42.76	48.72	52.01	53.33
Hydrogen, H_{daf},%	6	6.07	5.36	5.97	6.25	6.06
Nitrogen, N_{daf},%	1.0	1.0	1.17	0.72	0.14	1.4
Oxygen, O_{daf}%	43.69	42.78	39.83	44.39	41.43	38.51
Sulfur, S_{daf},%	0.23	0.11	0.23	0.14	0.1	0.13
Clorine, Cl_d, mg/kg	100	1500	2098	4479	603	5740
Calorific value						
Higher, Q^s_{daf}, MJ/kg	18.963	19.377	18.4	19.2	20.68	21.3
Lower, Q_{ir}, MJ/kg	15.767	15.016	17.11	17.99	19.36	20.06
Ash melting						
Initial deformation, t_a, °C	1200	1160	989	924	1200	810
Hemisphere, t_b, °C	1250	1180	1 203	1161	1252	1293
Fluid, t_c, °C	1330	1260	1 243	1224	1259	1328

Plant waste has some negative properties that complicate their use as fuel in standard equipment. Straw and stalks can have a high content of sulfur (0.02-0.7%), chlorine (0.02-0.6%) and potassium (800-26000 mg/kg), due to which harmful chemical compounds are formed causing corrosion of equipment and lead to the formation of a large number of aerosols, accompanied by high emissions of HCl and SO_2.

The main non-combustible component of ash is silicon dioxide SiO_2 (sand), which has a high melting point of 1400-1500 °C, but with the addition of potassium or sodium, the melting point can be reduced to 800 °C. Reducing the melting temperature of ash (850-950 °C) leads to slag and contamination of heat exchange surfaces, which can lead to overheating, reduced power and forced equipment shutdowns.

Maize stalks have a high water content at the time of harvest (50-60%), and also contain chlorine and alkali metals, which is close to the rate of "gray" straw. The melting point of ash from corn stalks (1050-1200 °C) is higher than for straw ash (800-1100 °C), and the sulfur content is lower. Sunflower stalks have high water content (60-70%) at the time of harvest, as well as a higher level of ash content (10-12%) and potassium content.

Various external factors, such as the waste collection season, the technology of raw material procurement, climatic conditions in the region and soil quality, crop rotation, as well as the amount of mineral fertilizers applied affect the quality of waste. That is why agricultural waste that is planned to be used as fuel must be certified. The presence of quality certificates and certificates of origin legalizes them on the market, and compliance with quality requirements will ensure the possibility of safe use in energy equipment.

[24] Fuel Properties of Ukrainian Corn Stover. V.O. Antonenko, V.I. Zubenko, O.V. Epik

5. Technologies and equipment

The specific fuel characteristics of agricultural waste require the use of specialized equipment and special technological solutions that can improve the quality of combustion and combustion efficiency in compliance with all environmental requirements.

A detailed overview of combustion technologies with an assessment of the advantages and disadvantages was provided in the manual on the preparation and implementation of natural gas replacement projects with biomass[25] [26]. Direct combustion is a well-established industrial technology and is characterized by its simplicity and affordability. Modern improvement of these technologies follows the path of solving the problems of environmental pollution, adaptation to the use of different fuels, increasing efficiency and application in cogeneration cycles. More complex technology is the gasification of biomass, which has not yet reached a wide commercial level and has a limited number of equipment manufacturers, but can be used under special conditions, including when using low-quality fuels.

The most common technology of agricultural waste incineration is a vibration water cooling grates (**Table 4**), less common are technologies of flare incineration of crushed biofuels and fluidized bed combustion. These combustion technologies are embodied in various types of heat-generating equipment, the thermal productivity of which covers a wide range of capacities from domestic boilers to power plants (**Figure 1-3, Annex 5**).

Table 4 - Combustion technologies and application features

Technology	Features of application
Bed combustion	
Fixed grate	hot water boilers and heat generators of periodic combustion, capacity up to 1 MW, manual and mechanized fuel supply, homogeneous composition and low fuel humidity
Chain grate	co-combustion with coal and different biomass, inhomogeneous fuel composition and fraction is allowed, used in the reconstruction of existing boilers with a capacity of up to 50 MW, including of CHP
vibrating and pushing water cooling grates	homogeneous fuel composition and fraction, used both in the reconstruction of existing boilers and in new boilers with a capacity of up to 120 MW, including at CHP, is the main technology of agricultural waste incineration
Dust (flame) combustion	co-firing in existing coal-fired boilers, homogeneous fuel with fine fraction, capacity over 100 MW, incl. of TPP
Fluidized bed (BFB, CFB)	co-combustion, inhomogeneous fuel composition and fraction are allowed, high content of moisture and harmful impurities are allowed, capacity over 30 MW, incl. of CHP

The technology of periodic combustion has become widely used in hot water boilers and hot air heat generators with a capacity of up to 1 MW. Fuel in the form of bales is loaded into a large combustion chamber, where combustion takes place, which can last up to 4-5 hours, after which the next portion of fuel must be loaded. The simplicity of construction, low level of mechanization and affordable price provide the basic requirements of farms and small processing enterprises in obtaining thermal energy. Heat energy can be used for heating residential and agricultural premises, as well as for the operation of drying chambers, grain elevators, as well as for the supply of heat energy to small heating networks. The main disadvantage of the periodic combustion of biomass is the insufficient level of combustion control, which negatively affects

[25] "Preparation and implementation of projects to replace natural gas with biomass for thermal energy production in Ukraine." Guideline/Ed. Geletuhi GG, 2016
[26] Biomass Combined Heat and Power Catalog of Technologies U. S. Environmental Protection Agency

emissions into the atmosphere during the ignition of the boiler. The need to use the equipment for loading medium and large bales significantly affects the possibility of using such equipment in municipal enterprises.

Figure 1 - General view of periodic combustion boilers

The technology of continuous combustion on moving grates allows organizing the combustion process effectively due to thorough mixing and adjustable duration of combustion, zone air supply and controlled temperature in the fuel layer. A significant advantage of this technology is the ability to burn pellets and baled straw, which does not require additional processing or preparation. Technological solutions for combustion on grids allow avoiding ash melting, provide the maximum burning of fuel and low emissions of polluting substances in the atmosphere.

One of the varieties is the technology of "cigar" combustion (**Figure 2**) with the afterburning of residues on the grate, which is effectively in boilers up to 10 MW. The advantage of the "cigar" combustion is the low level of electricity consumption and the absence of equipment in the technological cycle for mechanical grinding of straw bales into chips. Large bales of straw can be cut into several pieces and fed in portions into the boiler furnace. This reduces both investment costs and operating costs in the production of heat energy.

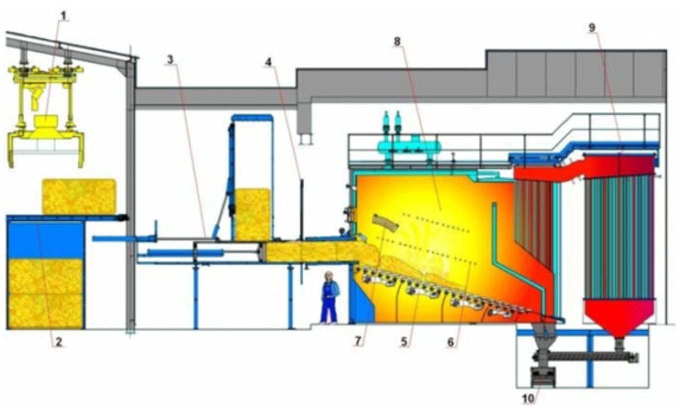


Figure 2 – Schematic structure of the boiler with the technology of the "cigar" combustion

Fluidized bed combustion technology as well as biomass dust combustion technology is generally used for co-combustion of biomass with coal and/or co-combustion[27] of different types of biomass at existing coal-fired power units with a capacity of more than 100 MW. Compared to others, this technological solution has low investment costs for reconstruction ($ 50-1500/kW), which allows to mix up to 20% of biomass to the main fuel without reducing power. Fluidized bed combustion technology allows adjusting a wide range of boiler power and the proportion of biomass in the mixture from 0 to 100%. The main limitations are the ability to provide adequate amounts of biomass in large quantities. These technologies are used mainly in power units that operate in supercritical parameters of steam - pressure over 200 bar, steam superheat temperature - 520-540 °C, which provides high efficiency of electricity production (**Table 5**). Examples of straw-fired CHP process

[27] The Handbook of Biomass Combustion and Co-firing

schemes in Denmark are given in **Annex 5**. It should be noted that Ukraine has a lack of experience in combining biomass with traditional fuels, and there are no available domestic technologies and equipment on the market. The biggest barrier to the development of co-combustion is the lack of a "green" tariff for biomass electricity from co-combustion.

The vast majority of companies supply ready-made technological solutions from fuel storage to a turnkey chimney. This approach minimizes the risks of inconsistencies in the use of equipment from different manufacturers, reduces the time of project implementation and establishes a single person responsible for the efficiency of the whole complex. Do not forget that the overall reliability of the object is determined by the reliability of the weakest link in the entire technological chain of production. Thus, when implementing projects, important attention should be paid not only to the main technological equipment (boilers, turbines) but also to auxiliary equipment - fuel depots, fuel supply systems, ash removal and gas cleaning systems, heat and electricity storage and supply systems. In Ukraine, European standard technological solutions with a high level of automation and mechanization can not be economically feasible. For their implementation in Ukraine, adaptation is needed based on real economic conditions.

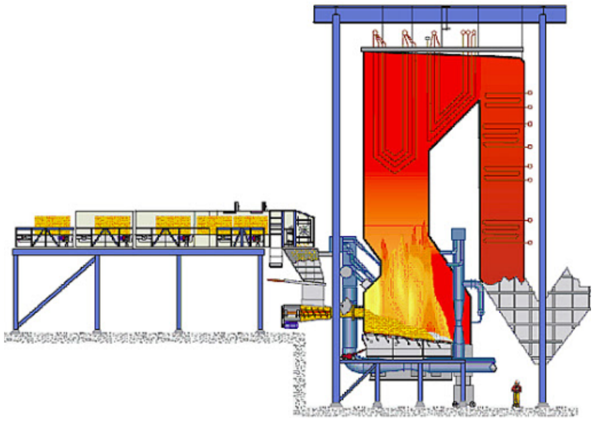


Figure 3 – Schematic structure of an energy boiler with combustion technology on a vibrating grate

Table 5 – Characteristics of power plants in Denmark using straw as fuel [28]

Name	Haslev	Rudkobing	Slagelse	Fynsvaerket	Mabjergvaerket	Masnedo	Enstedvaerket	Maribo	Avedore 2	Amagervaerket	Studstrupvaerket	Grenaa
Electric power, MW	5	2.55	11.4	35	28	9		10.6	275	80	2x350	19,6
Useful heat release, MW	13	7.5	28	75	0	0		22.5	-	250	2x455	40
Commissioning	1989	1990	1990	2009	1993	1996	1998	2000	2001	2009	2005	1992
Equipment supplier	Volund	B&W	Aalborg	Bioneer	Volund	B&W	B&W	FLS Miljo A/S	FLS Miljo, B&W, Volund	B&W	Babcock	Aalborg
Fuel	straw	straw	straw	straw	straw, chips, pellets	straw, тріска	straw, тріска	straw	straw, + coal	straw pellets+ coal	Straw + coal	Straw + coal
Fuel consumption, thousand tons	26	14	30	150	30	40	120	45	150	150	130	40
Boiler heat output, MW	20	11.2	31	118	39	36.4	80	37	100	350	Н.д.	88
Combustion technology	cigar, grate	vibrating grate	moving grate	vibrating grate	vibrating grate, cigar	vibrating grate	vibrating grate	vibrating grate	flame, grate	flame, grate	flame	Fluidized bed
Working pressure of desks, bar	67	60	67	110	67	92	210	102	310	185	250	92
Steam productivity, t/h	26.532	12.96	57.6	165.6	50.4	46.44	122.4	49.68	144	500,4	1033,2	104,04
Steam temperature, C	455	450	450	540	520	520	510	540	310	562	540	505
Electrical efficiency of CHP	19%	22%	25%	33%	-	25%	41%	29%	49%	23%	42%	22%
Boiler efficiency	88%	89%	89%	93%	90%	88%	92%	88%	94%	95%	-	-
Gas cleaning	fabric filter	fabric filter	electrostatic	fabric filter	fabric filter	fabric filter	electrostatic	fabric filter	electrostatic	electrostatic	electrostatic	electrostatic

[28] Bioenergy for electricity and heat – experiences from biomass-fired CHP plants in Denmark

The abovementioned comparative information on thermal power plants in Denmark using straw allows concluding that for plants with a capacity of up to 50 MW bed combustion on moving grates is used. The technologies of co-combustion with coal in a fluidized bed are used for higher capacities. High operating parameters of steam (pressure 67-200 bar, overheating temperature up to 455-540 °C) allow to achieve the efficiency of the boiler at the level of 89-93%, and the electrical efficiency of CHP in the cogeneration mode is on average 22-33%. It is preferable to use bag filters in flue gas cleaning systems, which can provide particulate emissions at a level not exceeding 20 mg/nm^3 meeting current regulatory requirements.

The supply of heat energy in the district heating network is an extremely important factor in the economic efficiency of CHP, the technological scheme of which is focused on the primary production of heat energy. The operation of CHP in the cogeneration mode allows increasing the efficiency at CHP up to 85%, which significantly affects the cost of production.

Table 6 is created on the basis of the analysis of practical implemented projects in the world. It provides information on the main manufacturers of boiler equipment for agricultural fuel combustion. Danish companies are the world leaders in the production of equipment for the combustion of agricultural waste. Analysis of 54 straw heating boilers in Denmark with a total capacity of about 250 MW allows us to conclude that the leaders are such manufacturers as Weiss, Linka, Danstoker. Typical is the capacity of 2-8 MW boilers using medium bale sizes. In 75% of cases, straw bales are shredded with the help of stationary straw shredders, and only in some cases, they are cut into pieces for further combustion. Fuel supply to the boiler furnace is carried out using hydraulic and screw fuel supply systems (**Figure 4**). The advantage of hydraulic systems is the low noise and mechanical wear of fuel elements.

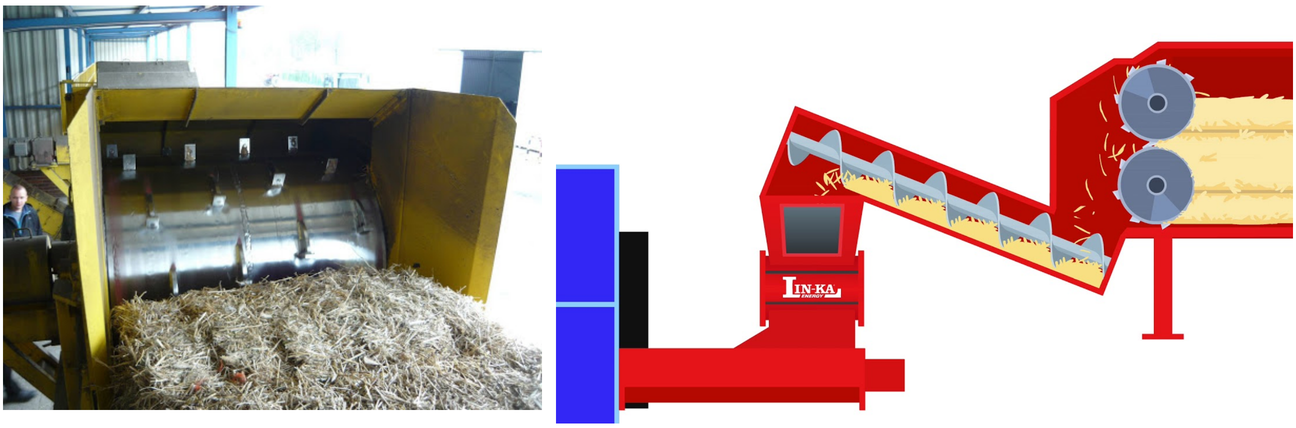


Figure 4 – Straw grinder and fuel feeding scheme

In 90% of cases, fuel storages are equipped with cranes for unloading and moving bales, which allows organizing their work in automatic mode effectively. With the help of cranes, from 1 to 12 bales can be moved at the same time, which significantly speeds up the time for unloading vehicles. Fuel storages of TPPs/CHPs can be equipped with several fuel depots or separate runs equipped with several cranes, which allows unloading several cars with a trailer at the same time. The use of wheel loaders is less efficient, requires free space in the warehouse for maneuvers, but is a less expensive measure at the investment stage (**Figure 5**).

In order to ensure control over the quality of combustion and compliance with environmental requirements, boilers are equipped with stationary automatic emission control systems. The combustion air supply is regulated automatically, depending on the oxygen content in the combustion products based on the signals of oxygen sensors.

Figure 5 - Mechanization of straw warehouses

Table 6 - Equipment Manufacturers for burning agrobiofuels

№	Name/Trade Mark	Thermal capacity, МВт				Web-адреса
		<0,1	0,1-1	1-5	>5	
1	Agro Forst					http://www.agro-ft.at
2	B&W Volund				x	http://www.volund.dk/
3	BWSC				x	https://www.bwsc.com/
4	D'alessandro	x	x	x		http://www.caldaiedalessandro.it/
5	Danstoker	x	x	x	x	http://danstoker.dk/
6	DP CleanTech				x	https://www.dpcleantech.com
7	Enerstena			x	x	http://enerstena.lt
8	EuroTHERM		x	x	x	http://www.eurotherm.dk/
9	FAUST	x	x	x		https://www.faust.dk/
10	Gizex		x			https://www.gizex.com.pl/
11	Granpal		x	x		http://granpal.pl
12	Heizomat	x	x			http://heizomat.de/
13	HERLT	x	x	x		http://herlt.eu
14	HOST			x	x	http://host-bioenergy.com
15	Justsen			x	x	https://justsen.dk/
16	KARA			x	x	http://kara-greenenergy.com
17	Komkont			x	x	http://komkont.com/
18	Kovosta				x	http://www.kovosta.cz/
19	LINKA	x	x	x		https://www.linka.dk/da/
20	MetalERG	x	x			http://kotlynaslome.pl/en/main/
21	Passat Energi A/S	x	x			https://passatenergy.com/
22	Polytechnik GmbH		x	x	x	http://polytechnik.com
23	PROTECH Sp. z o.o.	x	x	x		http://protech-wkg.pl
24	REKA	x				https://www.reka.com/
25	Skeltek	x				http://www.skeltek.dk/
26	STEP		x	x		http://steptrutnov.cz
27	Teisen	x				https://www.farm2000.co.uk/
28	Tenza		x	x		http://www.tenza.cz/
29	TTS Boilers			x	x	http://tts.cz/
30	Uniconfort		x	x		https://www.uniconfort.com/
31	Verdo		x	x	x	https://www.verdo.com/
32	VYNCKE			x	x	http://vyncke.com/
33	Weiss			x	x	https://www.weiss2energy.eu

It is obvious that the bed combustion in different types of grates will remain the main technology of energy conversion of biomass, and new powerful facilities that plan to use agricultural waste as fuel will focus on the use of imported equipment and technology.

In Ukraine, a high level of development has been achieved in the use of sunflower husks and pellets for both heat and electricity production. Domestic energy equipment and engineering solutions are widely used in existing boiler houses and CHPs. Existing experience, technical potential and technological capabilities allow mastering modern, efficient technologies and establish the production in Ukraine of specialized energy equipment for the burning of agrobiofuels. This process can be accelerated through close cooperation and collaboration with leading European companies and the experience exchange. An important argument in involving domestic producers in the implementation of investment bioenergy projects is the availability of additional economic incentives through the surcharge to the "green" tariff for electricity. Indirect additional benefits in such cooperation are the acquisition of additional knowledge and practical experience by domestic companies, providing jobs for the population, creating additional value and additional income by enterprises, development of related markets, and filling local and state budgets with taxes and fees.

6. Environmental aspects

Construction and operation of energy facilities cause a multifaceted impact on the environment. Current environmental legislation is aimed at preventing environmental damage, ensuring environmental safety, sustainable use and reproduction of natural resources. The purpose of the environmental assessment is to determine the level of impact, possible consequences and conditions of compliance with and ensuring the requirements of current legislation.

TPPs and CHPs with a thermal capacity of 50 MW and more can produce a significant impact on the environment and are subject to environmental impact assessment (OVD). Other facilities are subjected to a section on the evaluation of environmental impact (OVNS) in the project, according to DBN A.2.2-3-2014. The environmental assessment is carried out for the whole site and is a mandatory and necessary condition for obtaining further permits for emissions of pollutants into the atmosphere.

Environmental assessment includes all emission sources, which are divided into stationary and mobile (transport), as well as organized and unorganized. Emission sources are fuel and chemical reagent depots, fuel grinding or pouring areas, chimneys, ventilation systems, parking lots, etc. As a rule, the highest level of the environmental impact from the activities of fuel-burning facilities is associated with emissions of pollutants into the atmosphere. Expected pollutants are nitrogen dioxide, ammonia, hydrogen chloride, sulfur dioxide, carbon monoxide, substances in the form of suspended solids, non-methane volatile organic compounds, greenhouse gases, etc.

Permissible emissions of pollutants into the atmosphere are strictly regulated by state regulations in the field of environmental protection and depend on the period of commissioning, capacity, type of fuel, combustion technology and flue gas cleaning systems.

There are two different approaches for solving the problem of technical support of environmental requirements - primary and secondary measures.

Primary methods are the following: combustion mode, organizational, preparatory measures and others. These may significantly reduce the formation of harmful substances by affecting combustion in a combustion chamber.

Secondary methods are aimed at reducing the concentration of already generated emissions through the use of specialized gas cleaning equipment.

The most common is the integrated application of various methods that combine a set of measures to ensure quality requirements for fuel quality, the choice of special equipment for the selected fuel, the installation of additional gas cleaning equipment and compliance with the regime parameters.

The elemental composition of fuel has a decisive influence on the amount of pollutants in the combustion products. Given that agrofuels may have a higher level of nitrogen, sulfur, chlorine compared to wood biofuels, then for their safe use should be used appropriate technology and gas cleaning equipment.

The nitrogen in a fuel leads to the formation of nitrogen oxides NOx. To reduce them, the traditional mode methods are used that is the stage air supply, flue gas recirculation, moisture injection, reduction of excess air ratio. Primary methods have low efficiency; therefore, some secondary methods can additionally be used. Such methods are based on chemical purification of flue gases - oxidative, reducing and sorption.

The most promising is the reduction method with the use of ammonia (NH_3). Currently, two types of ammonia nitric oxide reduction are widely used in biomass combustion - the method of selective non-catalytic reduction (900-1200 °C) and catalytic (300-500 °C) reduction in the presence of a catalyst from oxides of various metals (titanium, chromium, vanadium). The efficiency of cleaning systems with such methods is 30-70% with the possibility of increasing to 90%. Due to the danger of using ammonia (high toxicity), urea is used instead of ammonia, otherwise: urea $(NH_2)2CO$. Non-catalytic recovery has economic advantages over catalytic recovery, which is used in large energy and industrial boilers and solid waste recovery boilers.

The presence of carbon monoxide (CO) in the flue gases indicates incomplete combustion of the fuel. The reduction of CO emissions is achieved by primary methods. Typically, this is the optimal design of the combustion chamber (providing sufficient time, temperature and stirring for complete combustion), fuel preparation (drying and/or grinding), efficient air distribution in the combustion chamber. High levels of CO emissions are observed in low-power boilers and boilers with periodic combustion, where there is no proper regulation of air supply and compliance with operating temperatures. The experience in Denmark shows that the transition to the use of straw-burning boilers with automatic supply has reduced CO emissions from 1.2% to 0.4%.

Sulfur (SOx) compounds pollute not only the air but also cause corrosion of the metal of power equipment. The main source of pollution by sulfur compounds is the combustion of coal and petroleum products, including in the joint combustion of biomass with coal, which is practiced in EU countries. There are two methods of purification of flue gases from sulfur oxides in the world: double alkaline desulfurization and semi-dry desulfurization.

Semi-dry desulfurization is a simple, relatively inexpensive, highly efficient system that covers a small area and is easy to operate. The technology of the semi-dry method of desulfurization with an efficiency of up to 95% is based on the supply of the sorbent in a suspended state in special reactors installed in front of bag or electrostatic precipitators. Slaked lime is introduced into the gas stream in the form of a powder or suspension, depending on the temperature of the gas stream. During the drying process, the desulfurizer reacts with sulfur dioxide in the flue gases, forming dry powder products that have no secondary contamination and can be reused. This type of desulfurization is used mainly for the purification of flue gases of boilers at TPPs and CHPs. The flue gas cleaning capacity of one tower can be used on steam boilers with a capacity of 50 MW.

As a result of the combustion of solid biomass, ash is formed, part of which enters the flue gas purification system, where they are purified from solid particles. As flue gas cleaning systems, the following technological solutions are usually used to ensure compliance with environmental standards, in particular: cyclones, multicyclones, wet inertial ash traps, electrostatic precipitators, bag filters.

Cyclones and multicyclones are mechanical separators, the principle of operation of which is based on the use of centrifugal forces. The multicyclone is a series of cyclones that operate in parallel, which reduces the size of the unit. The overall efficiency of the cleaning system is from 65% (for cyclones) to 95% (for multicyclones). Cyclones are also used as a pre-cleaning before the electrostatic precipitator or bag filter.

Electrostatic precipitators are widely used for the deposition of particles in the combustion of various types of biomass. An electrostatic precipitator is a dust collector in which the solid phase is separated from the gas in an electric field of corona discharge. This variant of gas cleaning is extremely effective (98 - 99.5%), and the level of efficiency is almost not reduced for particles with a size of 1 µm or less. The degree of the capture of the electrostatic precipitator corresponds to the best bag filters. Electrostatic precipitators have a very low aerodynamic drag. Wet systems are somewhat more effective at capturing very small particles, which may include toxic metals. A significant disadvantage of the gas cleaning system with an electrostatic precipitator is the significant capital costs and complexity of the operation. Installation of a flue gas purification system based on an electrostatic precipitator is economically feasible for biomass boilers with a capacity of more than 10 MW.

Dry gas cleaning with the use of bag filters made of a particular filter fabric allows achieving an extremely high level of cleaning efficiency from solid particles up to 99.99% and even for very small particles (less than 1 µm). As a rule, bag filters allow reducing the concentration of solid particles to 20-50 mg/nm^3, and in some cases even to 10 mg/nm^3, which is sufficient to meet environmental requirements. Experience in the operation of bag filters indicates that there is a risk of burning the fabric with unburned particles entering the filter. Bag filters are not recommended for use in small biomass boilers for safety reasons. The disadvantage of the system is also significant capital costs, high aerodynamic pressure and the risk of decommissioning due to wear or clogging of filter materials and condensation of water vapor.

Existing technologies for burning agrobiofuels allow ensuring the permissible level of pollutant emissions into the atmosphere by installing only gas cleaning equipment to remove particulate matter. The vast majority use bag filters. On powerful installations, including in the case of joint combustion of biomass with coal, gray and gas purification plants are used.

The first straw-fired power plants in Denmark 30-40 years ago had high emissions, and emissions of carbon monoxide and particulate matter exceeded the permissible values. Subsequently, the Danish Environmental Protection Agency proposed the following limit values for straw-burning boilers with a capacity of more than 1 MW: solids - 40 mg/nm^3; carbon monoxide - a maximum of 0.05%, O_2 - 10%.

There are no clearly defined requirements for installations below 1 MW, but design approval authorities typically use stricter criteria than for district heating plants up to 1 MW[29]. Emissions of decentralized CHPs in Denmark (**Table 5**), burning straw as a fuel were: CO - 0.05-0.2 from 12% CO_2, solids - 40-50 mg/nm^3, SOx - 280-300 mg/nm^3, NOx - 160-400 mg/nm^3. For several years, the Danish Institute of Technology has controlled emissions of various substances from district heating boilers with a capacity of 20-33 MW for the period 2002-2007 (**Table 7**).

Table 7 – Straw boilers for district heating

	Particulate matter mg/m^3	**CO ppm**	**NO_2 ppm**	**SO_2 mg/m^3**
32 MW 2001-2006	<0,1-1,1	37-153	271-331	85-161
33 MW 2002-2004	16-37	153-682	22-266	143-215
20 MW 2004	0,4-1,4	164-285	706-912	151-157

[29] Videnblade. Informationsblade om halm og trae til energiformal.

The large-scale use of straw for energy needs in Denmark required an in-depth assessment and determination of the actual emission for power plants. In 2007, the Danish Ecological Research Institute, together with a large number of experts, specialists from companies and universities, carried out in-depth measurements of pollutant emissions at various sites, including that use straw[30]. The developed research program included studies of both standard gaseous organic compounds and heavy metals, furans and aldehydes, polycyclic hydrocarbons, organic and ultrafine pollutants, and others (**Table 8**). In particular, studies were conducted at 6 CHP plants running on straw, and measurements - at 3 CHPs. There were no significant differences in emissions compared to 2000, and all differences were due to variations in straw properties. An important fact is that the content of mercury, cadmium and zinc were lower than in 2000 and were at the lower limit of measurement. The results of the comparisons confirm that emissions from straw combustion are higher compared to the combustion of gas and wood fuel, but all indicators were below the permitted values.

In Ukraine, there is a constant increase in environmental requirements and harmonization of domestic regulations with European ones. As a result, the current European environmental requirements are planned to be implemented in Ukraine[31]. Directive 2010/75/EU sets maximum emissions of pollutants into the atmosphere when burning clean biomass in large power plants with a total effective thermal capacity for fuel P> 50 MW. The requirements of Directive 2010/75/EU enter into force in the Energy Community for all large combustion plants after 31 December 2027. Directive 2015/2193/EC "On the limitation of emissions of pollutants into the atmosphere from medium combustion plants" introduced maximum permissible emissions of pollutants from existing and new power plants with a capacity of P = 1… 50 MW. In 2008, Ukraine introduced technological standards for permissible emissions of pollutants from large power plants with a nominal capacity of more than 50 MW, which indicate promising technological standards for emissions (**Table 10**) [32].

[30] Emissions from decentralised CHP plants 2007
[31] Peculiarities of application of normative documents on limiting the emission of pollutants during biomass combustion M.M. Zhovmir, M.O. Bud'ko
[32] About the statement of technological specifications of admissible emissions of polluting substances from thermal power plants which nominal thermal power exceeds 50 MW. Order № 541 of October 22, 2008 Ministry of Environmental Protection of Ukraine.

Table 8 – Emission factors for pollutants of thermal power plants and thermal power plants on straw Ошибка! Закладка не определена.

Pollutant	Emission factor	Emission factor in terms of volume	Min	Max	Number of measurements	Type and hazard class of the compound according to the Order of Ukraine #309	Limits, according to the Order of Ukraine №309
SO_2	49 g/GJ	107.8 mg/m^3	24	78	15	vapor and gaseous inorganic compounds, class II	500 mg/m^3
NO_x	125 g/GJ	250 mg/m^3	98	178	14	vapor and gaseous inorganic compounds, class IV	500 mg/m^3
UHC ©	< 0.94 g/GJ	< 2.068 mg/m^3	0.8	1.0	7	unburned hydrocarbons (class not defined)	
CO	67 g/GJ	147.4 mg/m^3	28	145	16	vapor and gaseous inorganic compounds, class IV	250 mg/m^3
N_2O	1.1 g/GJ	2.42 mg/m^3	0.8	1.9	6	Class not defined	
TSP	2.3 g/GJ	5.06 mg/m^3	0.1	7	13	The total content of suspended particles	50 mg/m^3
Cd	0.32 mg/GJ	0.0007 mg/m^3	0.002	0.69	7	Suspended solid particles (microparticles and fibers), class I.	0,2 mg/m^3
Hg	0.31 mg/GJ	0.00068 mg/m^3	0.10	0.57	7	Suspended solid particles (microparticles and fibers), class I.	0,2 mg/m^3
Zn	0.41 mg/GJ	0.0009 mg/m^3	0.40	0.43	2	Carcinogenic substances, II class	1 mg/m^3
PCDD/-F	19 ng/GJ	0.000042 mg/m^3	1.0	97	9	Polybrominated dibenz dioxins and furans, Substances classified as organic compounds, class II	100 mg/m^3
PAH (BaP)	125 mcg/GJ	0.00000028 mg/m^3	6	440	6	Polycyclic aromatic hydrocarbons, class not defined	
ΣPAH	5946 mcg/GJ	0.000013 mg/m^3	173	180	2	Polycyclic aromatic hydrocarbons, class not defined	
Naphthalene	12088 mcg/GJ	0.000027 mg/m^3	1238	40468	6	Substances classified as organic, class I	20 mg/m^3
HCL	56 g/GJ	0.00000012 mg/m^3	24	75	8	Class not defined	
HCB	0.11 mcg/GJ		0.10	0.15	2	Hexachlorobenzene, Class not defined	

Table 9 – Promising technological standards of allowable emissions for biomass

Substance	Thermal capacity (P), MW	Technological standard, mg/nm³	
		For new units	for upgraded units
SO_x	50 ≤ P ≤100	200	200
	100 < P ≤300	200	200
	300 < P	150	200
NO_x	50 ≤ P ≤ 100	250	300
	100 < P ≤ 300	200	250
	300 < P	150	200
Substances in the form of suspended solids, undifferentiated by the composition	50 ≤ P ≤ 100	20	30
	100 < P ≤ 300	20	20
	300 < P	10	20

In 2009, Ukraine introduced technological standards for permissible emissions of pollutants from boilers operating on sunflower husks, equipped with thermal power plants with a nominal thermal capacity of less than 50 MW[33]. The Ministry of Environmental Protection of Ukraine has adopted standards for maximum allowable emissions from stationary sources (**Table 10**).

Table 10 – Maximum Permissible emissions of pollutants from stationary sources[34]

Substance	Hazard class	Mass emission, g/hour	Permissible concentration, mg/nm³
Sulfur dioxide SOx (dioxide and trioxide) in terms of sulfur dioxide Oxides of nitrogen NOx (oxide and nitrogen dioxide) in terms of nitrogen dioxide	IV	> 5000	500
		< 5000	no limitation
Carbon monoxide CO	IV	> 5000	250
		< 5000	no limitation
Substances in the form of suspended solids, undifferentiated by the composition	-	> 500	50
		< 500	150
Chlorine Cl	II	> 50	5
Fluorine and its compounds in terms of HF	II	> 50	5
Chlorine compounds not belonging to class I, in terms of HCl	III	> 300	30
Cadmium and its compounds in terms of cadmium CD Mercury and its compounds in terms of mercury Hg	I	> 1	0.2

For existing installations, direct measurements are made and compared with the maximum allowable emissions. For new installations that have not been put into operation, the use of the results of environmental tests of equipment of manufacturers on the appropriate fuel is allowed when developing projects for

[33] Technological standards of permissible emissions of pollutants into the atmosphere from boilers operating on sunflower husk. Order 13.10.2009 №540. Ministry of Environmental Protection of Ukraine
[34] Standards for maximum permissible emissions of pollutants from stationary sources., Order 27.06.2006 №309. Ministry of Environmental Protection of Ukraine

environmental assessment. At the same time, the most common is the calculated method of estimating emissions on the basis of regulatory documents[35]. On the basis of the calculated gross emissions of pollutants, taking into account the location of emission sources and climatological conditions, the assessment of the dispersion of pollutants into the atmosphere is carried out. The result of this assessment is the development of the map with the concentrations of pollutants in the surface layer. In accordance with the obtained results, the permissible concentrations at the boundary of the sanitary protection zone are checked, and its size is determined/checked.

One way to implement the principles of sustainable development is to use low-emission fuels. It is believed that biomass is a renewable material, and all the energy contained in it is formed by photosynthesis by converting carbon dioxide from the air to carbon in plant cells. Of course, the combustion of biomass emits carbon dioxide and other pollutants, but this gas was absorbed during the initial growth of the burned biomass. Usually, for environmental assessment, perform the calculation of greenhouse gas emission reductions. Greenhouse gases include: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), halogenated fluorocarbons (HFCs) and fluorine carbohydrates (PFCs). The sum of greenhouse gas emissions with the corresponding coefficients is converted into the conditional equivalent of carbon dioxide CO_{2e}, which reflects the total emissions from planned activities. The content of carbon or carbon-containing compounds in the fuel determines the theoretical amount of carbon dioxide formation during complete oxidation. In practice, the amount of emissions is determined by the calculation method on the basis of averaged emission factors (g/GJ, kg/TJ)[36, 37], or on the basis of the elemental composition of the fuel (**Table 11**).

Table 11 – Emission factors of different types of agricultural waste

Fuel	C, %	Lower heating value, MJ/kg	K_{CO2}, g/GJ (kg/TJ)	K_{CO2}, tCO2/t
Straw (dry)	42.7	15.7	99 724	1.57
Rapeseed straw	48	17.6	100 000	1.76
Miscanthus	52	19	100 351	1.91
Sunflower husk	42.5	15.43	100 994	1.56
Rice husk	35.4	18.67	69 523	1.30
Stem of cotton	40	14.53	100 941	1.47
Stem of corn	50	15	122 222	1.83
Sunflower stalks (dry)	53.3	20	97 717	1.95

As a rule, leading energy companies strive for the highest standards of environmental management and implement environmental management standards in their enterprises according to ISO 14001: 2015. This standard requires the implementation of monitoring and accounting systems, compliance with which is confirmed by an independent international certified body.

[35] GDK 34.02.305—2002. Emissions of pollutants into the atmosphere from power plants..
[36] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf
[37] Collection of indicators of pollutant emissions into the atmosphere. Volume 1 Donetsk 2004.

7. Organization of energy production from agricultural residues

The success of a project largely depends on the initial stage of the work. Close cooperation with local authorities, farms, heat and electricity companies, as well as with financial institutions and the public are crucial in deciding to start the project.

Organizational and economic risks have a much higher impact on the project compared to technological risks, and therefore require in-depth, objective assessment and considered decisions. As a rule, the required assessment is performed within a business plan or feasibility study. It includes detailed organizational and technical solutions and possible risks analysis.

The present section reveals recommendations for the preparation and implementation of agro-waste projects and will help to increase their technical and economic efficiency.

To be or not to be? Cooperation with local authorities

Cooperation with local authorities and their readiness to support may become an incentive or obstacle for your energy project. Socio-economic and environmental issues are of interest to both government officials and the public. The public presentation of the project idea should cover the following issues: investment volume, types of activity and its danger or environmental impact, types and volume of production, job creation, taxes and fees, cooperation in related markets in the region, benefits and results of planned activities, corporate social responsibility.

It is worth to emphasize the mutual benefits from cooperation with local authorities in land, architectural and construction issues, utilities, tariffs, local taxes and fees, etc. One should remember that cooperation with local government bodies and population continues throughout the existence of the production facility.

Will agricultural waste become fuel?

Owners of agricultural residues and waste are small farms and large agricultural holdings. Despite world experience and scientific justification, many people are prejudiced against the use of such waste for energy purposes, based on the traditional approach to the exclusive use of waste and residues as organic fertilizer. At the same time, soil scientists recognize that the removal of plant residues from the fields does not lead to a critical and sharp decline in soil quality. The increase in volumes of entering of organic and mineral fertilizers allows increasing the volume of extraction of crop residues to 70% without deterioration of soil quality[38]. According to the data on the production and use of straw in scientific institutions and research farms of the Ukrainian Academy of Agrarian Sciences, a significant amount of it can be used for energy needs. If we also take into account the stems of corn, sunflower, rapeseed, then there is a reserve for thermal energy.[39]

Agricultural enterprises assess the benefits of being able to generate additional income from the sale of balances and weigh their own risks. Given the average yield of wheat 3-5.7 t/ha and the possible volume of straw harvesting 2-4 t/ha, the additional income per 1 ha may be 5-10% of the cost of wheat grain.

According to the ratings of the regions, Khmelnytsky, Cherkasy and Vinnytsia regions are in the lead in terms of the wheat yield - more than 5 t/ha, where there are prerequisites for the use of straw as a fuel. The highest yield of corn (7-7.5 t/ha) and the formation of residues are observed in the northern regions - Volyn,

[38] National report on the state of soil fertility in Ukraine.

[39] Scientific and practical approaches to use of straw and plant residues M.D. Bezugly, academician of UAAS V.M. Bulgakov, Corresponding Member of UAAS I.V. Greenwich, Corresponding Member of UAAS.

Khmelnytsky, Ternopil, Chernihiv regions. Even though the largest sown areas of sunflower are concentrated in the southern and eastern regions, but the highest yields (2.4-2.9 t/ha) are observed in Vinnytsia, Ternopil and Rivne regions. As a rule, there are several powerful agricultural companies in each region, and it is worth starting work with them. It is powerful companies that must provide the bulk of waste (over 30%) and be able to minimize possible supply risks.

The potential for agricultural waste generation, excluding plowed land and crop rotation, within a radius of 5 km is sufficient for the operation of a heating boiler with a capacity of 2-5 MW, and within a radius of 30 km is sufficient waste potential for CHP with a capacity of 10-15 MW of power (**Table 12)**. Increasing the delivery arm is a forced measure due to crop rotations and market conditions and leads to increased transportation costs. Thus, the closeness of a feedstock source is one of the key tasks when choosing a site for the project.

Table 12 – Average waste generation potential, kt

Feedstock	Waste yield, t/ha	Delivery radius, km			
		5	10	30	50
Wheat straw	2	3.9	15.7	141.3	392.5
	4	7.9	31.4	282.6	785.0
Corn stover	5	9.8	39.3	353.3	981.3
Sunflower stalks	3	5.9	23.6	212.0	588.8

Industrial fuel procurement requires significant logistics and financial costs. As a rule, small farms are not able to purchase their own machinery or provide harvesting, which deprives them of the opportunity to fully participate in the suppliers market. Thus, it is common practice to sell agro waste in the field without delivery. Often, harvesting of agro residues requires changes in existing agricultural practices, technology and new types of equipment. Unwillingness to change often becomes an obstacle to cooperation, and therefore requires considerable effort and time to compromise and find mutually beneficial solutions. New specialized procurement companies, rental and leasing of equipment are urgently needed in Ukraine. Agricultural enterprises or small farms can become not only allies or suppliers of fuel but also partners in the implementation of the energy project and share not only investment but also risks.

The following aspects should be taken into account when deciding on the choice of region for the project implementation:

- which agricultural waste will be the main fuel raw material;
- what wastes can be additionally used as fuel;
- available amount of waste within a radius of 50 km and concentration (density) of agricultural waste;
- the potential number of suppliers within a radius of 50 km, who they are and what their technical and financial capabilities;
- what is the existing practice in the region, procurement experience and interest in cooperation;
- what is the current level of prices for raw materials and waste and procurement services.

In order to find a compromise and to mitigate the negative impact of the removal of crop residues in favor of energy, scientists suggest the following measures that can be recommended to agricultural enterprises that intend to harvest agricultural waste for energy needs[40]:

– application of "no-till" technology of land cultivation;
– straw collection should be carried out only once every 2-3 years;
– plant sidereal crops on green fertilizers;
– leave stems and leaves in the soil;
– 2/3 of nutrient residues to leave + 1/3 to compensate by applying organic fertilizers;
– to ensure the return of ash from burning straw in the field;
– establish requirements for balanced soil fertilization;
– use other organic fertilizers: fermented mass from biogas plants, manure, etc.
– prefer to use corn stalks rather than wheat straw.

The readiness of agricultural enterprises to change and cooperate on long-term terms determines whether agricultural waste and residues will ever become a fuel.

What about the feedstock logistics?

The feasibility of agro-to-energy depends more on operating costs than on capital costs. The operating cost is mainly a fuel price. Minimization of fuel prices can be achieved by smooth organization and efficiency at all stages of the supply chain - procurement, warehousing and transportation. Organizational and technical aspects of harvesting the by-products of wheat, corn and sunflower were investigated in the previous position paper by UABIO and other sources[41].

There is no biomass market in Ukraine, which significantly limits the development and implementation of new energy facilities. The low level of motivation and low financial capacity of most agricultural enterprises force potential stakeholders to deal with logistics issues on their own. Practical experience of straw harvesting for energy needs on an industrial scale can be seen through the examples of enterprises engaged in the production of pellets and briquettes - Vinpeleta, Avertech, Bioenergy Vinnytsia[42]. In such companies, separate divisions have been established that deal with the logistics of raw materials and have their own equipment for procurement, warehousing and transportation. Procurement technology is proven and useful for further application in Ukraine. In addition, these companies are ready to provide procurement services on a commercial basis using their own equipment and experience.

The organization of logistics requires a large number and a wide range of equipment, depending on the volume of procurement, existing equipment and financial capabilities of enterprises. It is worth remembering that special equipment such as bale stackers or bale pickers are not widely used in Ukraine, and the number of offers on the market is limited. At the same time, there is a possibility to purchase used equipment from the EU after service, which is an attractive alternative solution.

Consider the example of the organization of harvesting on the example of grain straw. Judging by the productivity of combine harvesters 5-6 ha/h, the amount of straw in the roll can be 10-25 t/h. As a rule, the productivity of large straw balers is about 20-30 t/h. The use of bale stackers and baler pickers allows speeding

[40] Impact on soil removal of crop residues and possible measures to reduce such impact. On the impact on soil carbon of different ways of handling crop residues Authors: Jan Peter Leschen, Wageningen University and Research Center, The Netherlands Walter Elbersen, Wageningen University and Research Center, The Netherlands.
[41] Report on the analysis of technical solutions for energy production from solid biofuels. Task 3. IMR USAID Local Alternative Energy Project, Myrhorod.
[42] Comprehensive analysis of the Ukrainian market of biomass pellets. Manual. 2016. With the support of UNDP in Ukraine

up the harvesting. One harvester requires at least two bale pickers. When using wheel loaders, their number should be 3-5 times greater than the number of harvesters. When the distance to the storage is up to 5 km, it is needed to use two cars of 10 tons every 1.5 hours. With increasing distance to long-term storage warehouses up to 50 km, the required number of vehicles can increase to 6-8 units. It should be noted that under such conditions, there may be restrictions on warehouses capacity, and delays in unloading may occur. For these reasons, it is advisable to organize the storage of harvested raw materials directly in the fields with subsequent shipment after the end of the harvest season. The disadvantage of storing straw in the field is the need to allocate part of the field for the organization of warehouses in compliance with fire safety requirements and proper access roads for their use in the autumn-winter and spring period. There are also additional costs for overload and the need to organize the cover to protect raw materials from rainfall. The organization of logistics provides additional costs and time for transportation or independent movement of equipment, which should be carried out taking into account the organization of optimal routes and the use of special equipment. Similar recommendations apply to the use of other plant residues, in particular corn and sunflower stalks. However, it should be borne in mind that their moisture content is higher, and the weight of the bales will be greater.

Figure 6 – Bale stacker and unloading of bales from the platform of the automatic baler

To organize the effective logistics of crop residues, for example, straw, you should consider the following recommendations:

- **procurement:**
  - short time for harvesting and limited time for removal of agricultural waste from the field;
  - the possibility of harvesting various agricultural wastes, the collection of which is carried out at different times (rapeseed, wheat, oats, rye, corn, etc.);
  - the need to use modern, reliable and highly productive equipment in the required quantity;
  - the possibility of using used equipment;
  - full or partial availability of own equipment;
  - rental or leasing of equipment, involvement of specialized organizations with their own equipment;
  - procurement provided that the moisture content of raw materials does not exceed 15%;
  - the angle of the fields should be minimal, and the size of the fields and their concentration should be maximum;
  - minimization of soil pressure from the use of equipment;
  - the optimal amount of straw for harvesting should be at least 3 t/ha;
  - if the roll density is less than 1.5 kg/m, it is recommended to use an additional rake to double the rolls before pressing;
  - the recommended density of pressing straw into bales should be 120-140 kg/m^3;

  - height of bales: 0.7 and 1.3 m;
  - the length of the bales is 2.4-2.5 m.
- **transporting:**
  - bale harvesters, bale platforms and trailers with a length of 12-16 m for transportation within the field and at a distance of up to 5 km;
  - permissible height of cargo transportation 4.5 m (3x1.3 m or 5x0.7 m) height of loading the trailer up to 1 m;
  - carrying capacity of 10-15 tons;
  - cars with a trailer length of 7.5-8 m each;
  - early arrangement of convenient departures/exits from the fields;
  - reliable fastening and use of slings;
  - use of awning cover for transportation by public roads;
- **warehousing:**
  - storage height up to 8 m (6x1.3 m) with the possibility of automatic unloading of the bale picker platform;
  - temporary storage on the territory of energy facilities in closed warehouses;
  - use of cover (straw, film) for long-term storage in the field, storage under canopies;
  - arrangement of fire-fighting measures (breaks, lightning protection, overthrow);
  - use of front or telescopic loaders 1.5 t with an arrow boom of 10-12 m;
- **overall:**
  - overloads and equipment passes;
  - o service and maintenance availability in Ukraine, preferably 24/7;
  - o warehouses of spare parts;
  - o modern systems of navigation and fuel consumption control

Figure 7 – Loading and transportation of straw bales

Raw materials or improved biofuels?

Both raw materials (agro-waste, residues and by-products) in natural form and specially produced fuel from agro-raw materials can be used as fuel for energy facilities. In order to improve the physical, chemical and energy performance of raw materials, as well as to improve storage conditions, transportation or burning, the production of improved fuel - pellets and briquettes, dried or crushed biofuels, production of blended fuels with guaranteed performance is carried out. The practice of the use and production of pellets and briquettes from sunflower husk has become widely used, the production of pellets from straw, sunflower stalks and corn is developing[Ошибка! Закладка не определена., 43].

[43] Analysis of production of pellets and briquettes from by-products of corn for grain. Position Paper UABIO № 23

As a rule, the production of improved fuel is a forced measure, which leads to an increase in the price of biofuels, and accordingly, to heat and electricity cost rise. The low bulk density of raw materials requires large volumes of storage facilities and leads to high costs for transportation per unit mass/energy. Pelletization allows increasing bulk density by 5 times, which is especially relevant for sunflower husks or straw. The moisture content of more than 25% is not suitable for the long-term storage of straw. It can cause rotting and loss of fuel characteristics. In this case, additional drying or production of pellets may be an acceptable solution, in particular when using sunflower stalks and corn. The high water content of fuel and its low bulk density can create obstacles when it is used in the power equipment. Fuel can hang in hoppers, clog fuel systems or fly away with flue gases without burning. For example, in fluidized bed boilers, it is possible to use only granular fuel, and the use of fuel with high "sailing capacity" is not allowed. Energy, ecological and economic assessment of sunflower husk granulation[44] confirms that when transporting fuel up to 280 km, there is no need for granulation from all points of view and can only be a forced measure.

With appropriate organizational and technical solutions, economic feasibility should give preference to the use of fuel in the natural form at the lowest price.

What should be the organization of energy production from agricultural waste?

Specific features of agricultural waste, as a fuel, require not only special energy equipment but also special organizational approaches and technological solutions, which are primarily determined by the type of fuel. On the other hand, the process of production and supply of heat or electricity is identical to the use of other fuels, including wood biomass. The main differences concern the organization of warehouses, fuel supply, organization of combustion, gas cleaning and ash disposal. As a rule, investment costs for energy production using agricultural waste and residues as fuel are higher compared to wood biofuels. Therefore, from an economic point of view, it is advisable to build appropriate facilities with a capacity of more than 3-5 MW with a year-round heat load. Implementation of combined heat and power production can provide not only the high energy efficiency of production but also diversify products depending on market conditions.

To organize efficient energy production at boilers and thermal power plants, the following recommendations should be considered, according to the capacity:

- **construction site:**
  - availability of convenient access roads, taking into account traffic;
  - sufficient area for construction and placement of fuel depots;
  - the possibility of placing garages for storage of own equipment for procurement of raw materials;
  - providing fire breaks, protective and protective zones;
  - provision of the sanitary protection zone, not less than 50 m to residential buildings;
  - fire tanks or reservoirs with water supply;
  - fencing and limited access;
- **operational (cost) warehouses and long-term storage:**
  - organization of weight control of fuel delivery;
  - organization of closed operational warehouses with a hard surface and a fuel supply of up to 2 weeks;
  - organization of alternative open warehouses for long-term fuel storage in accordance with the available area;

[44] Energy, environmental and economic evaluation of the efficiency of solid biofuel use. E.M. Oliynyk.

- use of automated crane equipment in operational fuel depots in accordance with bale sizes and unloading scheme;
- height of fuel composition up to 8 m;
- the span width of the warehouse must be a multiple of the length of the bales (2.5 m), taking into account the passages and the length of the trailers (7.5-14 m);
- possibility of use of mobile front, telescopic loaders for internal warehouse overloads;
- organization of fire alarm and fire extinguishing system, lightning protection;
- organization of natural ventilation and natural lighting;
- periodic cleaning of all surfaces from dust - fire safety;

– **fuel supply and fuel preparation;**

- use of automated fuel supply lines/conveyors;
- advantage in the use of closed fuel supply systems to reduce noise and dust;
- the advantage of cutting bales, rather than chopping into chips;
- use of low-speed equipment for grinding;
- advantage in the use of hydraulic feed systems over augers;
- installation of fire dampers;

– **combustion technology:**

- burning in a layer on grates;
- use of water-cooling pushing and vibrating grates;
- zone air supply and flue gas recirculation;
- control of oxygen in flue gases through ⍰-probe;
- use of multicyclones and bag filters;
- automatic cleaning of heating surfaces;
- ash removal in airtight containers in closed warehouses;
- placement of wet ash removal systems in closed and heated rooms;
- stationary automatic control of CO and other compounds emissions in flue gases;

– **overall:**

- clear requirements and conditions of fuel delivery (sizes, admissible indicators, principles of price formation depending on quality);
- delivery schedule and payment terms;
- incoming fuel quality control - express analysis, sampling, periodic laboratory tests;
- automated fuel delivery accounting.

8. Best practices of agrowaste-for-energy

Poultry complex «Dniprovskyi» (Ukraine)

The boiler was put into operation in 2012 in Pershotravneve, Dnipropetrovsk region. As a result, the hen houses "Pershotravnevyi" and "Netelne" of the complex have been switched from natural gas to biomass. The boilers use straw bales of company`s own production saving up to 3.5 Mm^3 of natural gas per year.

Operator	Agro-industrial group of companies «Dniprovska»
Location	Pershotravneve, Dnipropetrovsk region
Thermal output	2x5 MW
Boiler	TTS Group (Czech Republic)
Fuel	Straw bales
Commissioning	2012

The two heating plants are equipped with 5 MW VESKO-S boilers from TTS Group (Czech Republic). The main fuel is rectangular straw bales of 200-420 kg, dimensions - 1.2 m width, 0.7-1.2 m height, and 2.2-2.5 m length. Fuel consumption is 5 bales per hour. Straw is harvested by own resources of the enterprise.

The straw bale is fed without the use of a large amount of electricity, almost silently and without dust. It is divided into smaller pieces and fed to the combustion chamber. The total electric power consumption of each boiler house is up to 215 kW. The flue gases are filtered in a bag filter, which provides the necessary environmental performance of the boiler.

Two workers who monitor the operation of the boiler and supply fuel from the warehouse on time are employed. The total duration of construction, taking into account the design, was 7 months.

Figure 8 – Straw-fired boiler plant. Poultry complex «Dniprovskyi»

Nyva Pereyaslavshchyny (Ukraine)

In 2017, Nyva Pereyaslavshchyny built a steam boiler house using baled straw as fuel[45]. Funds were provided under the EBRD - FINTECC program. The boiler house works on straw and produces technological steam for the production site in the village of Pereyaslavske. Straw is harvested on the company's own fields.

The boiler room is equipped with a Danstoker steam boiler with a steam capacity of 2.5 t/h and a Linka fuel supply system (Denmark). Design features and automation provide regulation of the boiler combustion, achieving a high-efficiency rate, making it burn almost all fuel. A cyclone-type filter is installed to clean the flue gases. Since 2009, the company has installed straw boilers at all nine company's pig farms.

Operator	Group of companies «Nyva Pereyaslavshchyny»
Location	Pereyaslavske, Kyiv region
Thermal output	2.5 t/h, 2 MW
Boiler	Danstoker, Linka-H
Fuel	Baled straw
Commissioning	2017

Figure 9 – Steam boiler plant «Nyva Pereyaslavshchyny»

District heating system in Trebišov (Slovakia)[46]

The new boiler house in the district heating system provides heat to the whole city, using straw bales and wood chips. The main equipment of the boiler house are two industrial boilers from the TTS Group, each with a capacity of 4 MW. The boilers are equipped with an electrostatic precipitator and a bag filter to reduce particulate emissions.

Operator	Národná energetická
Location	Trebišov (Slovakia) (25 000 population)
Thermal output	8 MW
Boiler	TTS Group (Czech Republic)
Fuel	Straw Bales(4 MW), wood chips (4 MW)
Commissioning	2016

The investor and operator of the new boiler house is a private company Trebišovská energyická sro. The heating system has undergone a complete reconstruction (11 km of new pipes). The initial system was

[45] http://visnik-press.com.ua/?p=83637
[46] http://www.trebisovskaenergeticka.sk/aky-mame-system-vykurovania

divided into several separate schemes, which depended on the use of natural gas into seven small boilers. These separate circuits were connected into one circuit, and heat production was moved to the outskirts of the city, where a new central heat source was built. Natural gas has been largely replaced by biomass, mainly straw and wood chips. Natural gas is used only as an additional heat source at the time of maximum consumption (i.e., only at extremely low temperatures during the winter).

Figure 10 – District heating system in Trebišov (Slovakia)

Power plant Miajadas (Spaine)

The plant Miajadas[47] was constructed in Spain, in 2010. This is the first power plant in Europe that can use two types of biomass (herbaceous and woody). This means that sources of biomass supply can be diversified. The project was developed as a research project with companies and technology centers in Spain, Finland and Denmark.

New methods to ensure the sustainability of energy production from biomass include the use of GPS and geographic information systems (GIS) for supply management, as well as special protocols and control systems that ensure efficient combustion without pre-drying the fuel. It provides about 100 jobs (25 of which right at the plant). Acciona has signed a total of 120 biomass contracts, 20 of them with agricultural and forestry companies and 100 with farmers.

Operator	ACCIONA
Location	Miajadas, Cáceres, Spain
Power	15 MW
Technology	Grate
Fuel	Herbaceous and woody biomass
Commissioning	2010

Key indicators:

- Average annual electricity production: 128 GWh.
- Annual biomass consumption is 110,000 tonnes
- Reduction of greenhouse gas emissions is 123,000 tCO_{2e} per year.

[47] https://www.acciona-energia.com/areas-of-activity/other-technologies/biomass/major-projects/miajadas-biomass-plant/

Figure 11 – Power plant Miajadas, Spain

Power plant Mostek (Czech Republic)[48]

The power plant uses pellets from agricultural biomass, which are produced directly in the territory of the power plant. The steam boiler with a fluidized bed with a nominal thermal capacity of 17.2 MW provides operation of the condensing turbine with intermediate extraction of steam with a capacity of 4.9 MW. The design of the boiler allows burning not only agricultural biomass but also wood chips, sewage sludge, etc. Diversification of sources allows optimizing electricity supply.

Operator	RSJ Investments, Dewarec
Location	Northern Bohemia, Czech Republic
Power	4.9 MW
Technology	boiler with a fluidized bed, 17.2 MW
Fuel	Herbaceous biomass (straw and hay pellets)
Commissioning	2014

Figure 12 – Power plant Mostek, Czech Republic

Key indicators:
- electricity production = 38,600 MWh/year
- fuel consumption (straw and hay pellets) = 40,000 t/year
- own granulation unit

[48] https://www.mostekenergo.cz/index.php/o-projektu.html

Annexes

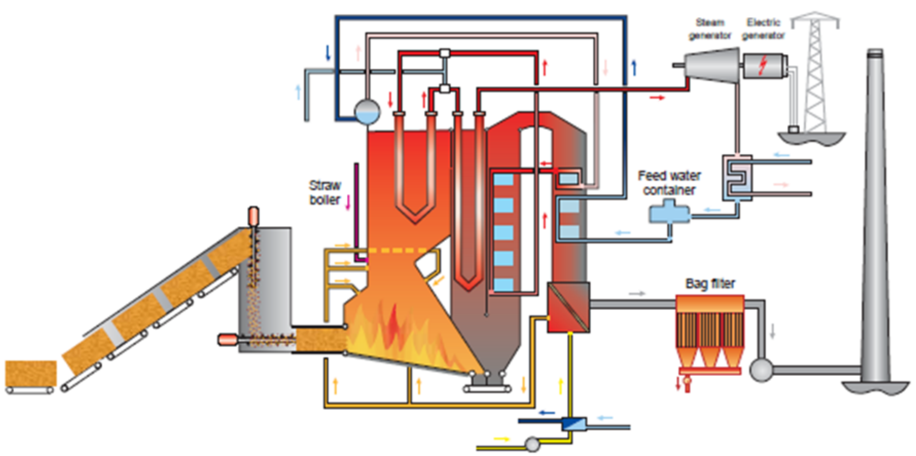
Annex 1 – Classification of solid biofuels by origin and sources of biomass according to (DSTU EN ISO 17225-1 2014. Table 1)

Annex 2 - Technical characteristics of baled fuel from straw, reed canary grass and miscanthus. (DSTU EN ISO 17225-1 2014. Table 10)

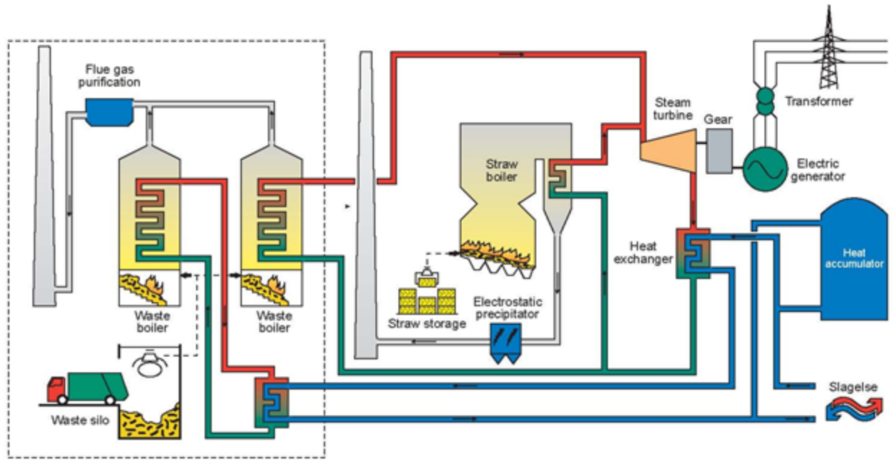
Annex 3 – Typical values of indicators characterizing the properties of some species of husks and mallows (DSTU EN ISO 17225-1 2014).

Annex 4 – Typical values of indicators characterizing the properties of straw that does not contain grain, or contains it in small quantities, fresh reed canary grass, miscanthus (DSTU EN ISO 17225-1 2014).

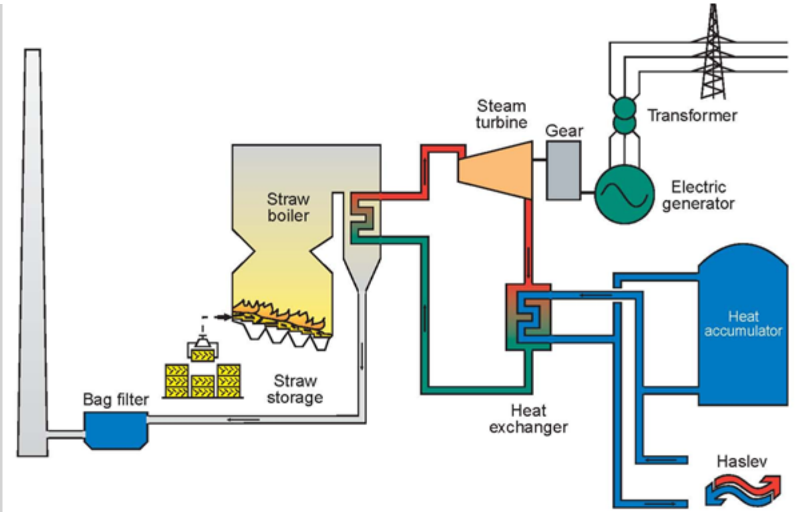
Annex 5 – Schematic solutions of CHP using straw in Denmark



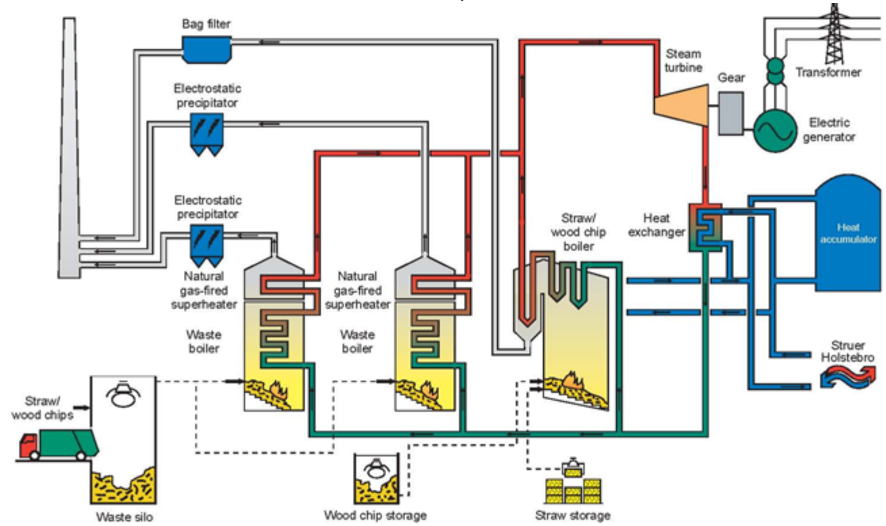
Scheme of a boiler for burning chopped straw on a grate



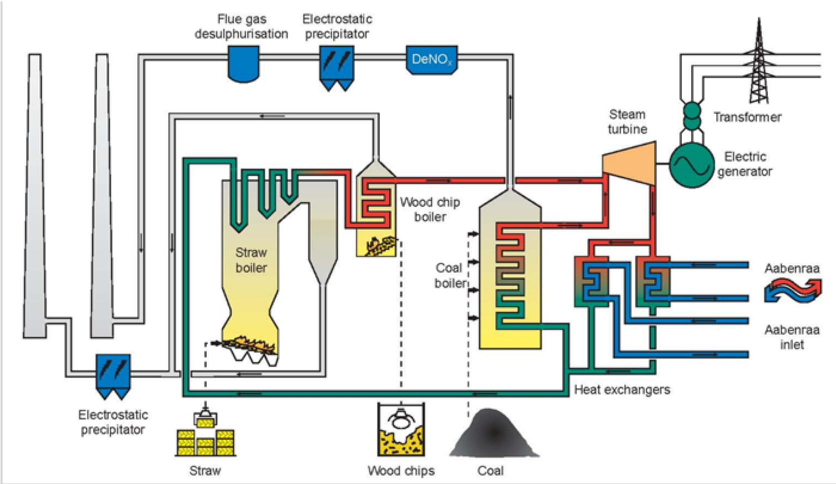
Scheme of Slagelse CHP with parallel co-combustion of shredded straw and solid waste in separate boilers



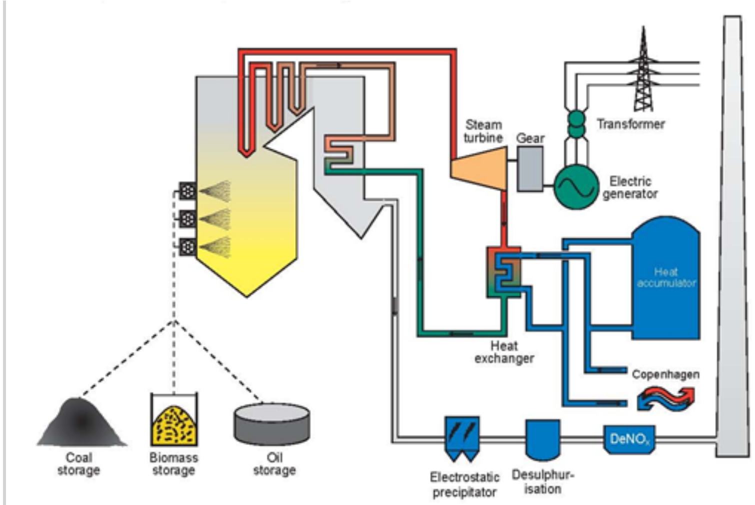
Scheme of block CHP Haslev with burning of chopped straw



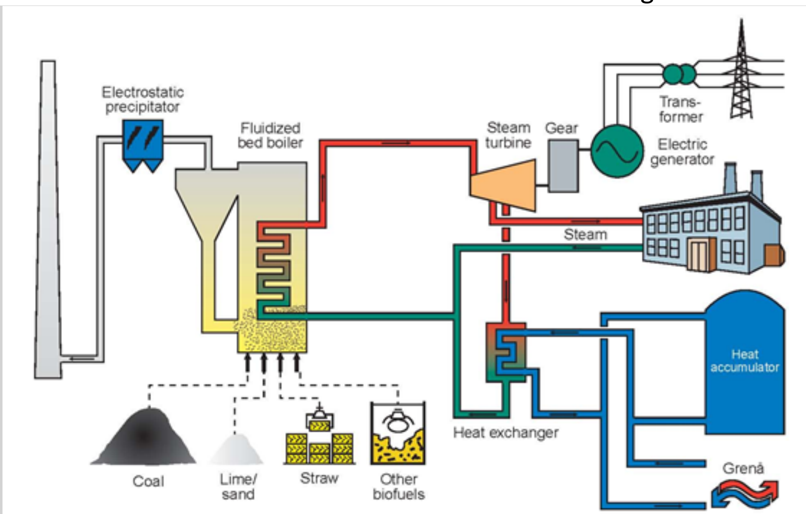
Holsebo CHP scheme with co-combustion of shredded straw and wood waste, and separate MSW



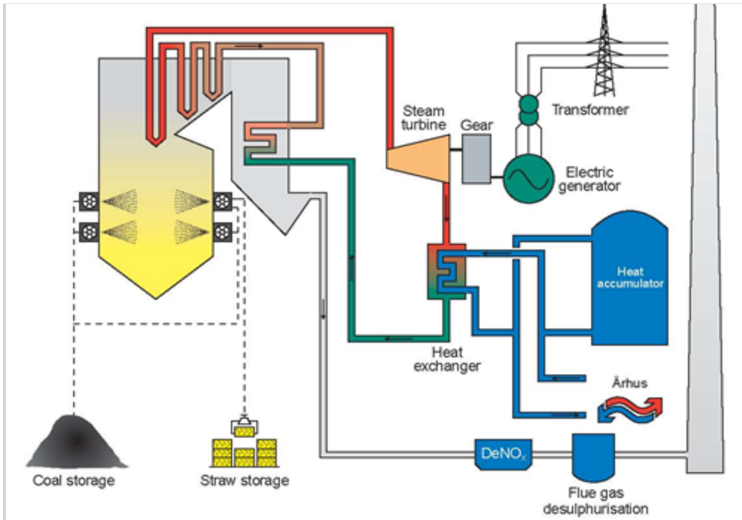
Aabenraa CHP scheme with parallel co-combustion of shredded straw and wood waste to control steam overheating



Copenhagen CHP scheme with dust co-combustion of crushed straw with coal in one burner



Scheme of CHP Grena with co-combustion of straw with coal in a fluidized bed boiler



Scheme of Arhus CHP with dust co-combustion of crushed straw with coal in separate burners