Advanced biomethane production from ligno-cellulose materials

ANALYTICAL NOTE No 2

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Table of contents

Acronyms

AD
Anaerobic digestion

bcm
Billion cubic meters

bcme
Billion m^3 of natural gas equivalent

CAPEX
CAPital EXpenditure

CC
Cover Crops

CEL
Cellulose

CHP
Combined Heat and Power

CSTR
Continuous stirred tank reactor

DES
Deep Eutectic Solvents

DM
Dry Matter

EBA
European Biogas Association

EMDE
Emerging market and developing economies

FL
Fuel and Lubricant

GHG
Greenhouse Gas

GTSU
Gas transmission system of Ukraine

HMF
Hydroxymethylfurfural

HSEL
Hemicellulose

IEA
International Energy Agency

IRR
Internal rate of return

LCOE
Levelized cost of energy

LFG
Landfill gas

LGN
Lignin

MSW
Municipal Solid Waste

n.a.
No Data Available

NVZs
Nitrate Vulnerable Zones

OF
Organic fraction

OPEX
Operating expenses

RED
Renewable Energy Directive

SSSU
State Statistic Service of Ukraine

UABIO
Bioenergy Association of Ukraine

VAT
Value-added tax

VS
Volatile Solids

Introduction

The purpose of the Analytical Note is to assess the potential opportunities for using ligno-cellulosic agricultural raw materials for the production of advanced biomethane in Ukraine.

Biogas and biomethane production remains one of the main trends in the energy policy of both European countries and Ukraine. In the EU, a new ambitious program of the European Commission REPowerEU[1], was launched in 2022, according to which it is planned to replace 20% of natural gas imported from the russian federation with biomethane by 2030, and subsequently increase biomethane production to over 100 billion m^3 per year by 2050.

Currently, the EU is experiencing a boom in the development of the biomethane sector – biogas brought to the quality of natural gas, which can be fed into gas pipelines, transported, stored and used on a par with natural gas. In particular, the EU plans to increase biomethane production from 3.5 billion m^3/year in 2021 to 35 billion m^3/year in 2030[2]. Priority support is given to biomethane production from waste and residues that do not compete with food and feed.

According to the EU Renewable Energy Directive (Directive (EC) 2018/2001, or RED II)[3], the contribution of liquid biofuels and biogas to the EU target for renewable energy consumption in transport is counted double, according to energy content, if these liquid biofuels/biogas are produced from feedstocks listed in Annex IX (Article 27). It is important that straw, husks, cobs cleaned of kernels of corn and other ligno-cellulosic materials used for biogas/biomethane production are raw materials from Part A of Annex IX of RED II, which makes them a priority raw material.

Until now, the use of crop residues for biogas and biomethane production has not been widespread in Ukraine, although at some biogas plants it was partially added to the main types of raw materials, such as sugar beet pulp, manure, etc. This is due to both technological factors associated with the complexity of processing such raw materials and economic factors associated with the low profitability of the common concept of electricity generation from biogas.

With the opening of opportunities to sell the produced biomethane on the premium market of renewable biofuels in European countries, the focus of biogas production projects in Ukraine is shifting towards the production and export of biomethane. At the same time, the traditional and most widely used types of raw materials in Ukraine, such as corn silage and sugar beet pulp, are not sustainable according to Directive (EU) 2018/2001, and therefore the demand for biomethane from these types of raw materials and its price are low. Therefore, there is a need to find sustainable types of raw materials, among which the most significant may be crop residues. Crop residues include a wide range of plant leftovers (straw, vegetable tops, etc.) with different characteristics, however the biggest share, especially in Ukraine, is refered to ligno-cellulosic types, such as straw and corn stover. **For the purposes of this Analitycal Note, hereafter the term "crop residues" will mean ligno-cellulosic types of crop residues (straw, corn stover).**

The pretreatment of lignocellulosic biomass such as straw or corn stover is a crucial step of biogas production. Its goal is to break down the complex structure of lignocellulose to allow the access to cellulose and hemicellulose for active components, which will subsequently convert those polimers into simple sugar molecules through enzymatic or acid saccharification.

The involvement of crop residues for large-scale biomethane production will require generalization and deepening of knowledge about the features of such raw materials from the point of view of technologies and economics of biogas production, which is what this analytical note is devoted to.

Definitions and terms

SECTION 1

Key definitions and terms

Directive (EU) 2018/2001 (RED II) provide the following means for cellulose containing materials:

> **'Ligno-cellulosic material'** means material composed of lignin, cellulose and hemicellulose, such as biomass sourced from forests, woody energy crops and forest-based industries' residues and wastes;
>
> These types of materials can be processed to biomethane via thermochemical technologies, however are out of the scope of this Analitycal Note.
>
> **'Non-food cellulosic material'** means feedstock mainly composed of cellulose and hemicellulose, and having a lower lignin content than ligno-cellulosic material, including **food and feed crop residues, such as straw, stover,** husks and shells; grassy energy crops with a low starch content, such as ryegrass, switchgrass, miscanthus, giant cane; cover crops before and after main crops; ley crops; industrial residues, including from food and feed crops after vegetal oils, sugars, starches and protein have been extracted; and material from biowaste, where ley and cover crops are understood to be temporary, short-term sown pastures comprising grass-legume mixture with a low starch content to obtain fodder for livestock and improve soil fertility for obtaining higher yields of arable main crops.

From the list of materials refered to as "non-food cellulosic materials" **straw and stover** are the most relevant to the scope of this Analitycal Note. Husks are widely used in Ukraine for heat production in unprocessed or pelletized forms by oil extraction plants themselve. Grassy energy crops such as ryegrass, switchgrass, miscanthus can be relevant as well if harvested in the later stages of vegetation in dry form, but for today these crops occupy a tiny share of lands in Ukraine and harvested mostly for production of biomass used for heat production. Cover or ley crops have a similar features to corn silage with low lignin content, that is not relevant to the purpose of this Analitycal Note. Industrial residues from food and feed crops are presented in Ukraine mainly by sugar beet pulp and oil press cake, that are also not relevant to the purpose of this Analitycal Note.

Anaerobic digestion means the process that includes a series of biological conversion processes in which microorganisms break down biodegradable material in the absence of oxygen: hydrolysis; acidogenesis; acetogenesis; and methanogenesis. The biogas produced contains methane (50–70%), carbon dioxide (30–40%), and other gases.

Crop residues are a part of the above-ground and underground organic matter created by crops, which includes by-products and post-harvest residues[4]. In general, **by-products** are residues that are not waste. Particularly in crop production, by-products are a part of the above-ground organic matter created by plants, which is collected when a combine separates the mature grains of a crop, and consists of straw and chaff. **Post-harvest residues** are a part of the above-ground and underground organic matter created by plants that remains in the field after a combine separates the mature grains of the crop. It consists of the plant's root system and stubble.

According to the definition of Ukrainian legislation[5], **biomethane** is biogas that, due to its physical and chemical characteristics, meets the requirements of regulatory legal acts for natural gas for supply to the gas transportation or gas distribution system or for use as motor fuel. Biomethane is obtained by upgrading biogas, which includes the removal of CO_2 and other impurities. Modern upgrading technologies ensure biomethane production containing 97-98% CH_4.

Overview of the current status and prospects of using crop residues for biomethane (BM) production

SECTION 2

Every part of the world has significant scope to produce biogas and/or biomethane. Potential for biogas or biomethane by regions and feedstock source is shown in the **Fig. 2.1** by assessment of International Energy Agency[6] in billions of cubic meters of natural gas equivalent (bcme).

The biggest potential belongs to Brazil, Africa in total, China, India, and the United States. The potential is formed by plant residues including cereals and grains residuals, sugar crops, roots and tubers residuals, and oil and protein production residuals, livestock waste, other biological waste, and woody biomass for thermal gasification.

Crop residues together with animal manure are the largest sources of feedstock for all regions, particularly in developing economies where the agricultural sector often plays a prominent role in the economy. For example, in Brazil, there are large volumes of maize and sugar cane residues coming from its sugar and ethanol industries. In India, where the agricultural sector contributes around half of overall employment, the vast majority of biogas potential comes from sugar cane, rice and wheat crop residues.

The biogas supply potential in the United States and Europe is divided among crop residues (mainly corn residues from the ethanol industry in the USA), animal manure and MSW.

Globally, the costs of producing biogas lie in a relatively wide range between 8 to 32 USD/GJ **(Fig. 2.2).** Around 70-95% of the total biogas costs are for installing biodigesters, with the remainder involving feedstock collection and processing costs. There is huge variability, as feedstock can be

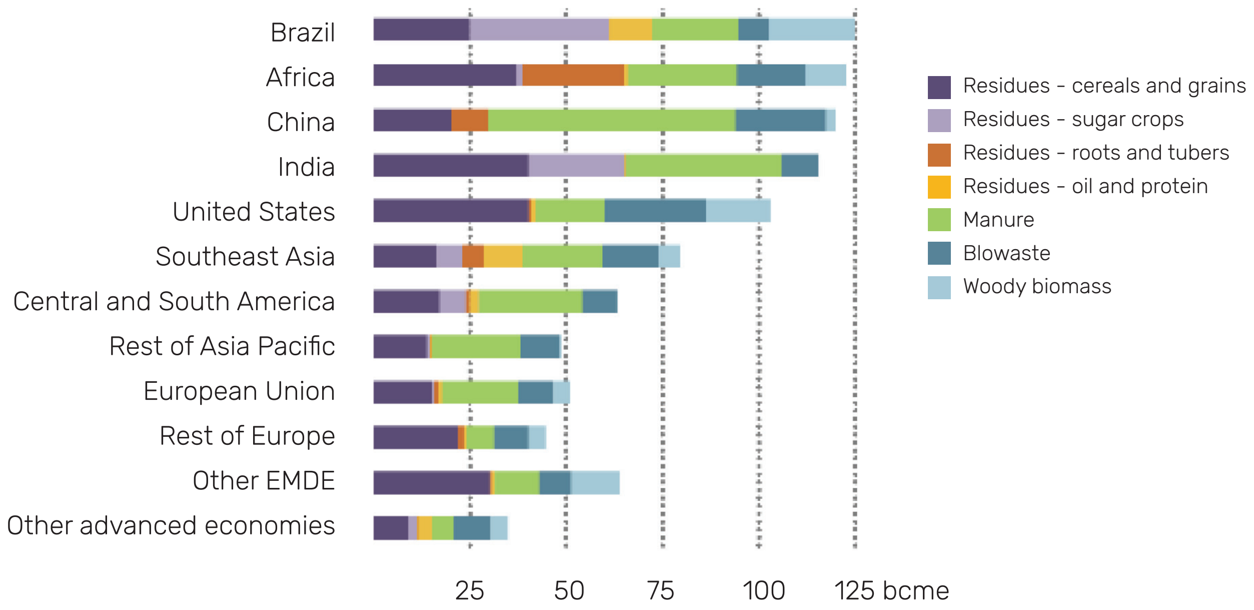


Fig. 2.1 – Potential for biogases by region and by feedstock type, 2024[6]
(EMDE = emerging market and developing economies)

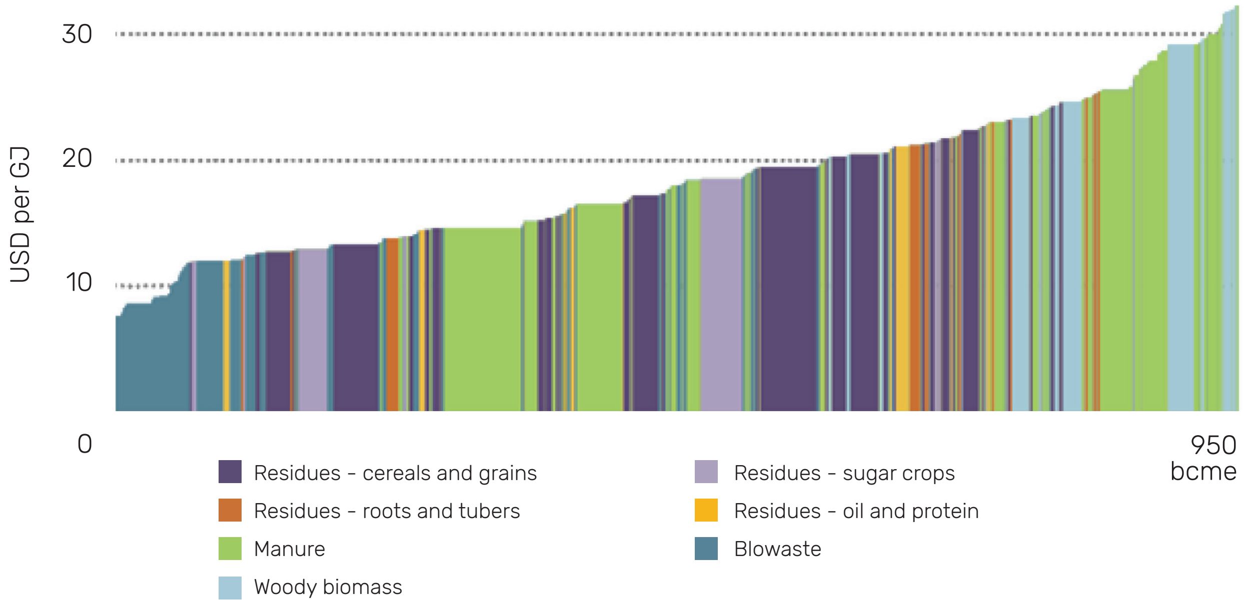


Fig. 2.2 – Supply cost curve of global biomethane potential by dominant feedstock, 2024[6]

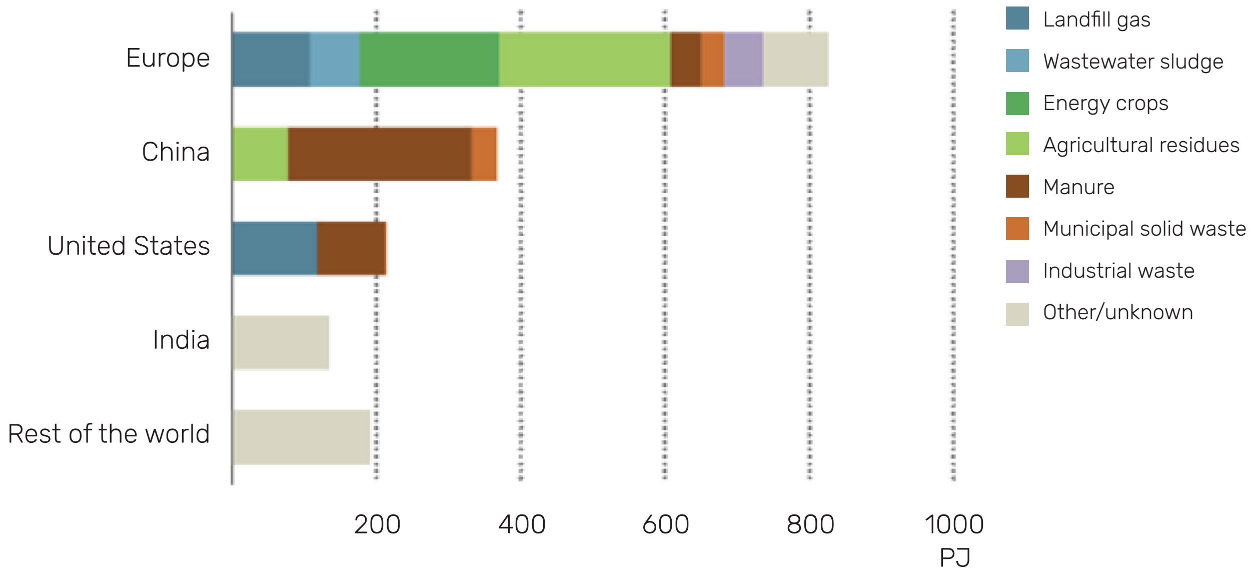


Fig. 2.3 – Feedstock use for production of biogases by selected country and region, 2023[6]

zero-cost or even negative in cases where producers of waste are obliged to pay to dispose of their waste, whereas in other cases "gate fees" for certain agricultural feedstock may be as high as USD 100/tonne in some regions.

The costs of producing biogas from agricultural crops lie in the range between 12 to 25 USD/GJ. It should be noted that IEA's curve integrates technology and feedstock costs. Technology costs include the biodigester only, i.e. excluding any costs for equipment to transform biogas into power and heat.

Actual feedstock utilization for production of biogas and biomethane is shown in the **Fig. 2.3.** It can be seen that agricultural residuals are used mainly in Europe and China.

Europe represent the most universal set of the feedstock for biogas production including landfill gas (LFG), waste water sludge, energy crops, agricultural residues, manure, MSW, and industrial waste.

Biogas and biomethane will play an important role in the European Union's (EU) ambition to achieve net zero GHG emission by 2050. Via the REPowerEU Plan, the European Commission has set a target to produce 35 billion cubic metres (bcm) of biomethane annually in the EU by 2030, providing a renewable and domestically-produced source of gas that can act as a direct substitute to fossil natural gas across many sectors of the economy.

Total production of biogas and biomethane in 2023 amounted to 22.1 bcm or 234 TWh of energy[7]. While biogas production remains important and relatively stable, biomethane is the fastest-growing segment of the market. European countries produced 4.2 bcm or 44 TWh of biomethane in 2022. This figure grew to 4.9 bcm or 52 TWh in 2023, representing an increase of 18%. Europe's production capacity for biomethane grew from 5.5 bcm/year in 2022 to 6.1 bcm/year in 2023 and 6.4 bcm/year by the first quarter of 2024.

An information regarding agriculture residues use in European countries is still limited. **Fig. 2.4** from EBA statistical report 2024 illustrates in mass percentages (wet weight) the relative use of different feedstocks for biogas production in 18 European countries. The feedstocks categories are divided among agricultural residues, manure, sequential and energy crops, sewage sludge, organic fraction of municipal solid waste (OFMSW), and industrial solid waste. It should be noted, that in several countries, no distinction could be made between agricultural residues and manure. For those countries, manure was included by EBA in the agricultural residues category.

It can be seen that the share of agricultural residues in the feedstock is large for those countries where the division between crop residues and animal waste was not provided. This may mean that in general the share of crop residues in biogas feedstock remains small in comparison with manure. Among the countries presented the distribution between manure and agricultural residues, the leaders in the use of agricultural residues are Belgium (>25% by wet weight) and Poland (20% by wet weight). It can also be seen that the use of crop residues is still unsignificant in Ukraine.

On the other hand, there is a clear trend towards the use of agricultural residues for biomethane production. **Fig. 2.5** from EBA statistical report 2024 shows the number of newly installed biomethane plants in Europe every year, overall and for each different feedstock type. Since 2017, almost no new plants have been established to run on energy crops. EBA believes that "this change partly reflects the fact that growth in biomethane production is no longer located primarily in Germany, with more plants instead being built in France, Italy, the Netherlands and Denmark. Whereas a large share of biomethane plants in Germany run on energy crops, plants in the countries current-

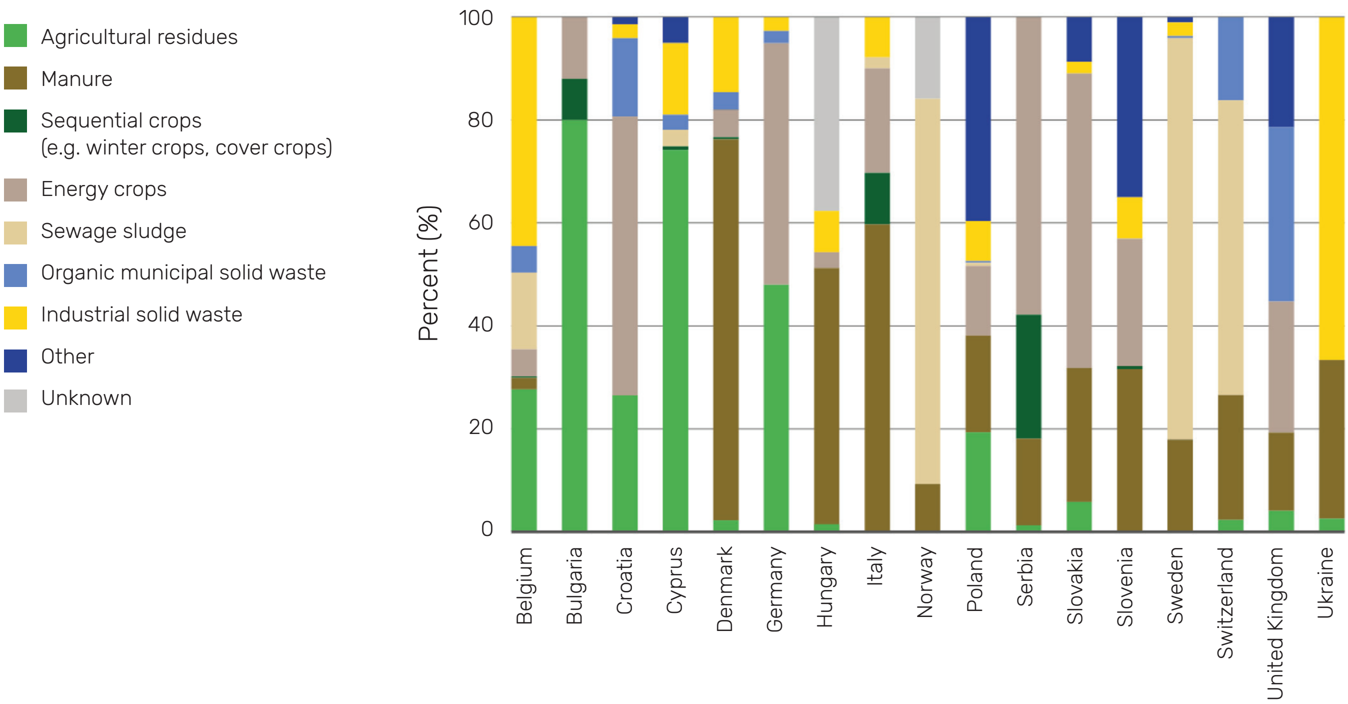


Fig. 2.4 – Relative use of different feedstock types for biogas production in selected European countries in 2023[7]

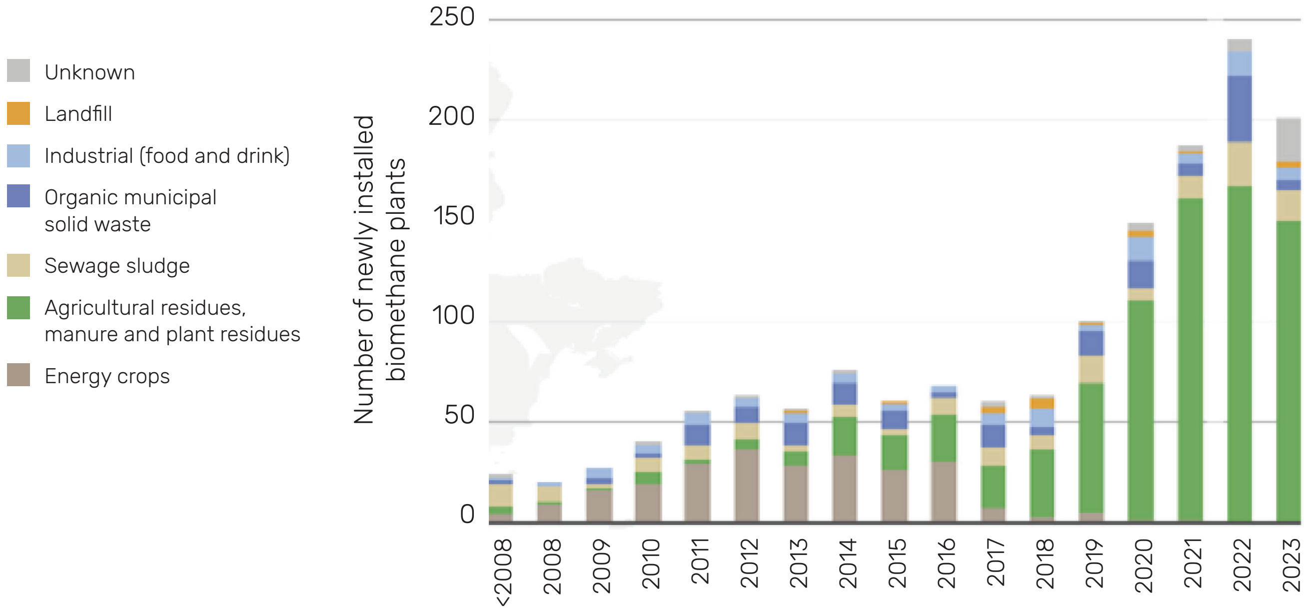


Fig. 2.5 – Number of new biomethane plants in Europe per feedstock type, 2008-2023[7]

ly leading growth in the sector run principally on agricultural residues and to a lesser extent also on organic municipal solid waste, sewage sludge and industrial waste". It should be noted that in this case agricultural residues include both plant residues and animal waste.

In 2022, consortium Gas for Climate published a study[8] estimating the potential for biomethane production in the EU-27 (plus Norway, Switzerland and the United Kingdom). The EU-27 potential in 2030 was estimated to be 41 bcm, increasing to 151 bcm in 2050 if the full sustainable biomethane potential can be realised. The estimated potentials for the EU-27 plus Norway, Switzerland and the United Kingdom was 45 bcm in 2030 and 165 bcm in 2050.

Biogas and biomethane can be produced from a diverse range of feedstocks. Two main biomethane production technologies include anaerobic digestion combined with upgrading the biogas, and gasification. Gasification means thermal gasification, which converts dry woody or lignocellulosic biomass and solid waste, and hydrothermal gasification (also known as supercritical water gasification), which is particularly well suited to the treatment of water-based organic wastes and effluents.

Almost all biomethane in Europe today is produced via anaerobic digestion. Thermal gasification with biomethane synthesis is currently at a demonstration scale. Hydrothermal gasification is at an industrial demonstration stage, with initiatives underway in several European countries. The potential to scale up both technologies is large in the medium to long term (2030 and beyond).

Agricultural residues are materials that are left over in the field, following the harvesting of the main crop (e.g. cereal straw). Agricultural residues are suitable for either anaerobic digestion or thermal gasification. However, in the context of this study, the feedstocks have been assigned to anaerobic digestion only, which is already commercially deployed at scale. However, in the future, hydrothermal gasification can further extend the scope of feedstocks suitable for biomethane production including agricultural residues.

The total biomethane potential per country was calculated considering an assessment of the availability of each feedstock and its conversion yield to biomethane through the assigned biomethane conversion technology. For agricultural residues, animal manure, industrial wastewater, sequential crops and sewage sludge the potential was estimated using a 'bottom-up' method, based on current statistical data of European and national level and projections up to 2050 considering trends in population, land area/crop production or livestock numbers.

The feedstock potentials reflect technical constraints (e.g. share of the theoretical feedstock potential that can be realistically mobilised) and where relevant environmental constraints (e.g. soil preservation), to derive a sustainable potential. The sustainable potential was further reduced to take into account existing non-energy uses, to ensure

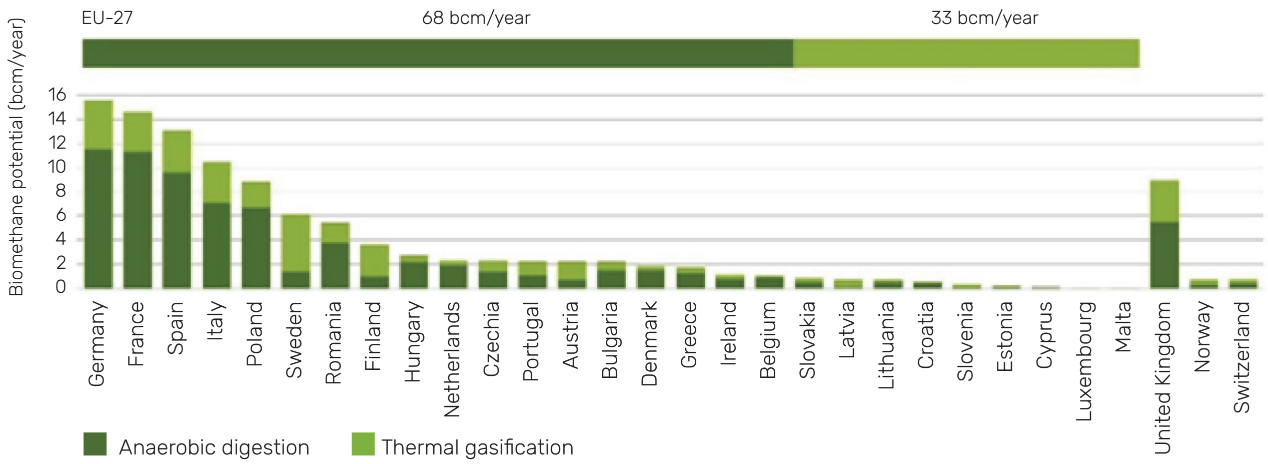


Fig. 2.6 – Biomethane potential (bcm/year) in 2040 per country and technology[8]

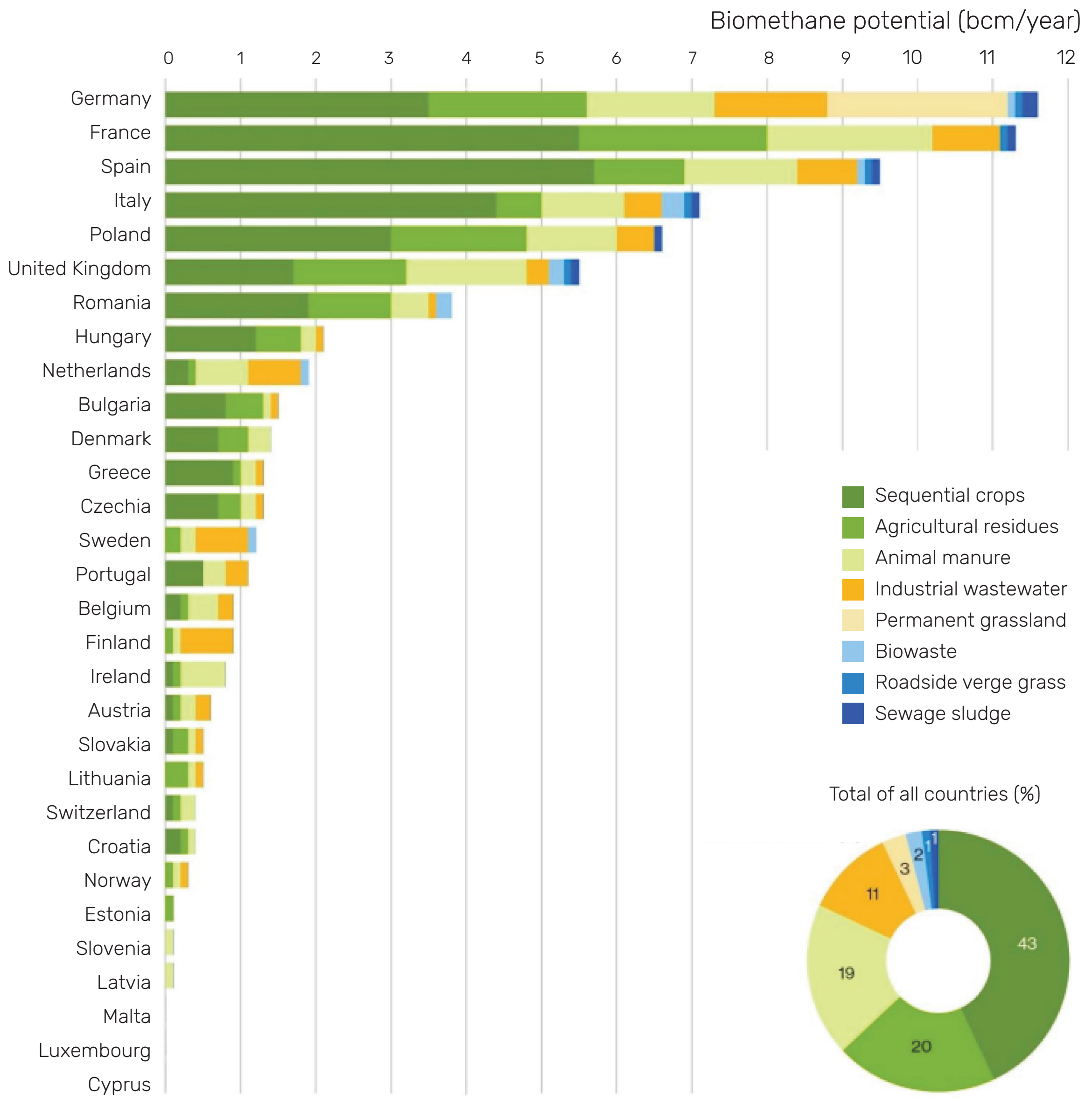


Fig. 2.7 – Biomethane potential (bcm/year) per country and total of all countries in 2040 for anaerobic digestion[10]

that the use of the feedstock for biomethane production does not impact these existing uses and lead to indirect impacts.

A biomethane potential of 111 bcm was estimated for 2040 **(Fig. 2.6)**, of which 101 bcm relates to the EU-27. This potential is made up of 74 bcm anaerobic digestion (67% of the total) and 37 bcm thermal gasification (33% of the total). The European countries with the highest potential in 2040 are Germany, France, Spain, Italy and the United Kingdom. Collectively, these countries represent over 50% of the total biomethane potential. A high potential is also seen in Poland.

As it was already mentioned the total potential of **74 bcm** is estimated for **anaerobic digestion** in 2040, of which 68 bcm relates to the EU-27. The top 5 countries include Germany, France, Spain, Italy and Poland **(Fig. 2.7)**[9]. Key feedstocks in 2040 are sequential crops (43%), as well as agricultural residues (20%) and animal manure (19%). Collectively these feedstocks represent 82% of the total.

The countries with the highest agricultural residuals potential in 2040 are France (2.5 bcm), Germany (2.1 bcm), Poland (1.8 bcm), United Kingdom (1.5 bcm), and Spain (1.2 bcm).

Types and properties of crop residues available in Ukraine

SECTION 3

Main types of crop residues

A significant amount of crop residues is generated annually in Ukraine as a result of the cultivation of the main crops. Among the lignocellulosic types of crop residues, the most common in Ukraine include **straw of cereal crops**, such as **wheat, barley; corn stover, sunflower stalks and heads, rapeseed straw and soybean straw (Table 3.1).** Given the smaller cultivation areas of other crops in Ukraine such as oat, rye, rice, buckwheat, etc., they generate lower volumes of plant residues suitable for biomethane production.

Table 3.1 – Main types of crop residues in Ukraine

Crop	Residue type
Wheat	Straw (stalks and leaves)
Barley	
Corn	Stover (stalks, leaves, husks, and cobs)
Sunflower	Stalks and heads
Rapeseed	Straw (stems, leaves, pods)
Soybean	

Wheat straw

Wheat is the crop with the largest sown area in Ukraine. It is grown in all regions of Ukraine, but more in the central, southern and eastern parts, with a drier and warmer climate.

Wheat straw (***hereinafter referred to as straw***) is the most common type of crop residue, which is widely used in various areas, including:

as bedding material for animals keeping (Fig. 3.1), including pets (straw pellets),

as a substrate for growing mushrooms in native or additionally crushed forms,

as a biofuel in baled (Fig. 3.2) or granulated/briquetted forms,

as a substrate for composting or vermicomposting,

as a raw material for biogas/biomethane production,

as a building material,

as a source of cellulose for paper production, etc.

Fig. 3.1 – Straw after harvest

Fig. 3.2 – Straw in round bales in the field

Technologies for collecting straw in the field, baling, shredding and granulating/briquetting, unlike many other types of crop residues, are commercially developed and widely used. Therefore, straw can be considered as a technically available raw material for biogas production. However, given the rather high competitive demand for straw in other areas of application, such a resource has, on the one hand, competitive pricing, and on the other hand, it can be a limited resource in certain areas and farms.

Given the fact that such straw is usually collected in warm, dry weather, its composition and properties are quite invariable. The dry mass of straw with a moisture content of 15-20% is well stored during the year in a baled form under cover, and is also suitable for the production of granules and briquettes from it. This makes straw a promising raw material for the technological process of biogas production.

Corn stover

In recent years, corn for grain (corn) in Ukraine has traditionally occupied significant areas of sown land, second among cereals only to wheat. Corn is grown in almost all regions of Ukraine, but most notably in the central, northern, and western regions, which are characterized by relatively higher soil moisture content. Therefore, crop residues of corn can be another important type of raw material for biogas production. At the same time, unlike straw, corn stover in Ukraine are rarely collected from the fields and used in other areas of activity, which makes it a raw material with relatively low competitive demand. Howevere, the practice of collecting corn stover in Ukraine exists. The production of pellets from corn stover is known, in particular in the Odessa region. Corn stover can also be a raw material for the production of the 2nd generation bioethanol, however, such technologies are not yet developed in Ukraine.

Corn stover, which is formed during the harvesting of corn grain, contains the bulk of the aboveground part of the plant, which is cut by a combine harvester. It contains various parts of the plant, including stalks, leaves, cobs and husks **(Fig. 3.3).**

The main feature of using corn stover as raw material for biogas production is the unpredictability of its composition, which depends on the corn variety, the harvest period, and weather conditions. Corn is harvested for grain at different times, depending on the variety, place of cultivation, and sowing dates. The moisture content of different parts of corn is heterogeneous and decreases rapidly 120 days after sowing. In Europe, the typical corn harvesting period is September-November. Often, farmers harvest corn in December-January, or even later, which is due to certain production needs and economic feasibility.

During harvest, corn stover **(Fig. 3.4)** are often wetter (W > 30%) than grain (standard moisture in the EU W14%), but after grain harvesting, moisture from corn stover evaporates intensively, including due to wind[11]. In addition, the moisture content of corn stover is highly dependent on weather conditions during harvest, and heavy rainfall can lead to very unfavorable conditions for biomass harvesting and its subsequent energy use. Ensuring proper storage of corn stover as a raw material for biogas throughout the year is a more difficult task than for

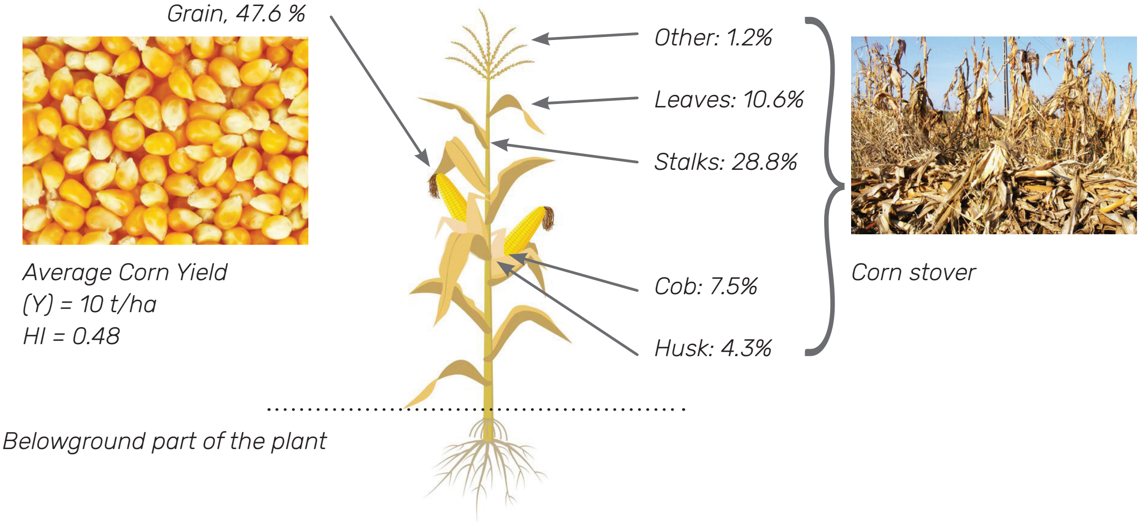


Fig. 3.3 – Different aboveground parts of the maize plant and their dry matter distribution

Fig. 3.4 – Corn stover in a field after harvest

Fig. 3.5 – Corn stover in round bales

straw. If the moisture content of the corn stover collected in bales **(Fig. 3.5)** exceeds 25%, it may rot over time, which will deteriorate its quality and lead to significant losses of dry matter, especially when the bales are stored outdoors. In the study[12] it was shown that open storage of corn stover bales results in a loss of 10 to 23% of dry matter, depending on its initial moisture content. Drying corn stover in the field in the fall to a moisture content of ≤20% acceptable for baling is often not possible[13], and therefore is not predictable.

For the effective production of pellets from corn stover, its moisture content should be within 10-15%. This moisture level ensures optimal pressing, pellet strength and reduces the risk of mold formation during storage. Therefore, when granulating corn stover, there will be a need for its preliminary drying, which accordingly increases the energy costs for the preparation of such raw materials.

An alternative is the collection, grinding for subsequent ensiling of the wet mass of corn stover (W=30-45%), which can be implemented in practice[14]. However, for effective ensiling this moisture may not be enough and additional moistening of such mass will be required in order to ensure sufficient sugar release from corn stover and sufficient pressing in the silo to create anaerobic conditions in bulk. Collection of wet biomass from the field may also increase ash content in it, due to the inclusion of a larger mass of soil, which may negatively affect the technological processes of biogas production.

In summary, it can be said that the use of corn stover as a raw material for biogas production will require more thorough approaches to its harvesting and storage, and the characteristics of corn stover may not be predictable from season to season, which makes such raw material to a certain extent risky for biomethane projects. A strategy to minimize these risks may lay in adapting the technological process of biogas production to the use of corn stover of variable composition, which is possible.

Sunflower crop residues

Sunflower is the main oilseed crop in Ukraine. Traditionally, most sunflowers are grown in the central, southern and eastern parts of the country. In Ukraine, the sunflower harvest period begins in August and ends in November, with the main crop being harvested in September-October[15].

Sunflower stalks **(Fig. 3.6)** after cutting the seed heads (baskets) are usually further cut, crushed and left in the field. However, such stalks can be harvested, for example, by a self-propelled forage harvester equipped with a header for harvesting coarse-stemmed crops[15], for further use. They can be used as biofuel[11], as a material for making paper[16], although such practices are not widespread, particularly in Ukraine. Therefore, sunflower stalks are an available biomass for biogas production, with virtually no competitive demand.

Sunflower stalks, heads (without seeds) and mixtures of stalks and heads are fibrous materials with low protein content and very variable composition due to differences in maturity and proportions of different residue fractions[17]. Similar to other types of crop by-products, the characteristics of the stem mass and heads depend on the place of cultivation, the period of harvesting and weather, soil and fertilizers. Also, the quality characteristics of the harvested sunflower by-products are significantly affected by the technology of harvesting and storage.

Considering that sunflower stalks can remain in the field in an uncut state for some time, it is possible to ensure their harvesting at a sufficiently low humidity, which will make such biomass suitable for long-term storage during the year with relatively predictable characteristics. The main disadvantage of the concept of using sunflower stalks as a raw material for biogas production is the low profitability of their harvesting, due to the low yield of such biomass per one hectare.

Soybean straw

Soybeans, as a rule, take second place in Ukraine in terms of sown areas among industrial crops, after sunflowers. Soybeans are grown to a greater extent in the central and western regions. In terms of its basic properties, soybean straw is similar to wheat straw, it is quite easy to bale, and therefore

Fig. 3.6 – Field after sunflower harvest

Fig. 3.7 – Soybean harvest

can have similar applications. Typically, soybeans are harvested when the grains reach a moisture content of approximately 13-15%, the leaves have fallen, the beans have become dry, and the stems and beans have turned brown.

The typical soybean harvest period may vary depending on geographical location and local climate. In Ukraine, in most regions, the harvest takes place from late summer to early autumn, usually from late August to October[18].

Direct cutting of soybeans using combine harvesters is the most common method of harvesting soybeans in Ukraine and the world **(Fig. 3.7)**. In this case, the straw is separated from the soybean grain in the combine itself and scattered across the field. The method of separate harvesting for soybeans, often called two-phase harvesting or swathing and picking up, where the crop is first cut into windrows and then later picked up by a combine, is indeed rarely used for soybeans. Soybean straw when harvested from the field is usually dry, so it is well suited for baling. Therefore, soybean straw can also be considered as a potential raw material for biogas production with predictable characteristics.

Rapeseed straw

Rapeseed ranks third in terms of area sown among industrial crops grown in Ukraine. The main reason for the popularity of rapeseed cultivation is the opportunity to sell it on the foreign markets. In 2023, Ukraine exported 3.7 mln tons of rapeseed, having harvested a total of 4.5 mln tons[19]. The leaders in rapeseed production are Khmelnytskyi, Ternopil, Odessa and Kherson regions. A lot of rapeseed is also grown in Vinnytsia, Volyn, Dnipropetrovsk, Lviv and Mykolaiv regions. In Ukraine, mainly winter rapeseed is grown (> 96% of all areas under rapeseed).

The timing of rapeseed harvesting usually depends on several factors, such as climatic conditions, geographical location and compliance with the requirements of a particular rapeseed variety. The rapeseed harvesting **(Fig. 3.8)** process usually takes place in the summer period. However, the specific timing may vary depending on each region and rapeseed hybrid. Typically, rapeseed is harvested in Ukraine in July–August. Rapeseed is harvested, as a rule, by combines, with the straw scattered in the field **(Fig. 3.9).** Given that the harvest is carried out in the summer, rapeseed straw can be harvested in a sufficiently dry state, suitable for baling and further energy use, including biogas.

Fig. 3.8 – Rapeseed harvesting

Fig. 3.9 - Rapeseed straw in the field

Characteristics of crop residues as raw materials for biogas production

From the point of view of anaerobic digestion technology, untreated lignocellulosic agro biomass is a relatively complex raw material, which is due to the following main properties:

> *strong hydrophobic properties*
>
> *high (non-optimal) C:N ratio*
>
> *high lignin content and low bioavailability of organic matter*
>
> *low moisture*

As a rule, the use of crop residues for biogas production requires the use of technologies for their pre-treatment before fermentation, as well as the use of additional, complementary types of raw materials, usually rich in nitrogen.

Hydrophobicity

The hydrophobicity of straw – its resistance to absorbing water – is primarily due to its biochemical composition and surface structure, which are typical for lignocellulosic biomass.

Hydrophobicity prevents liquid from penetrating the porous structure of straw fibers, which contain air. The hydrophobic properties of untreated straw are manifested over a long period of time, which makes such material buoyant and prone to flotation and clogging of the upper layer of technological tanks.

Although the absolute density of straw fibers is greater than the density of water **(Table 3.2)**, the presence of air in their porous structure does not allow such material to settle in technological tanks and bioreactors of the "wet" type.

Table 3.2 – True density of lignocellulosic material

Crop Residue	True Density, g/cm³
Wheat Straw	1.30–1.50
Corn Stover	1.35–1.45
Sunflower Stalks	1.20–1.40
Rapeseed Straw	1.25–1.45
Soybean Residue	1.30–1.45

At the same time, the porosity of different types of crop residues can be different and depends on the internal structure of the stem and other parts of the plant and the structure of lignocellulosic complexes. The internal porosity of straw fibers can be 50-70%[20].

Among the types of crop residues, wheat straw, rye straw and rice straw are characterized by the highest level of hydrophobicity **(Table 3.3)**. Corn and sunflower stalks, rapeseed and soybean straw are comparatively less hydrophobic. A high level of hydrophobicity will require the use of fairly intensive pre-treatment methods, including mechanical, thermal or chemical, to make such biomass suitable for anaerobic digestion in hydraulic-type technological systems.

Table 3.3 – Hydrophobic properties of some crop residues [21, 22]

Crop Residue	Hydrophobicity Level	Key Hydrophobic Factors	Water Absorption Behaviour
Wheat Straw	High	High lignin, waxy cuticle, silica	Poor wettability
Corn Stalks	Moderate–High	Moderate lignin, less waxy	Moderate
Sunflower Stalks	Moderate–High	Waxy surface, rigid	Slow swelling
Rapeseed Straw	Moderate	Moderate lignin, thinner wax	Moderately hydrophobic
Soybean Residue	Low–Moderate	Lower lignin, porous	Hydrophilic
Barley Straw	High	High silica, waxy cuticle	Poor

The main factors determining the hydrophobicity of straw and other crop residues include:

> *high lignin content,*
>
> *surface coating with a waxy cuticle,*
>
> *cellulose crystallinity,*
>
> *silica (SiO_2) accumulation,*
>
> *closed cell structures.*

Lignin is an aromatic polymer that fills the space between cellulose and hemicellulose, and is the most important factor in hydrophobicity. Strongly hydrophobic due to its non-polar, aromatic structure. Lignin acts as a natural water-protective barrier and structural support for plant biomass fibers.

The outer surface of straw (especially stems and leaves) is covered with a cuticle. The cuticle consists of a cuticular membrane that is insoluble in water with detergents, covered and impregnated with soluble waxes. The best-known component of the cuticular membrane is the polyester polymer cutin, which consists of hydroxyl acids linked by ester and epoxy bonds[23]. The cuticular layer strongly repels water, similar to the natural "plastic" layer **(Fig. 3.10)**.

Cellulose has amorphous and crystalline areas. The crystalline areas are densely packed and resistant to water penetration. Although cellulose itself is hydrophilic, its structure in straw limits the access of water.

Silica (SiO_2) often accumulates in the epidermis of straw, particularly wheat and rice. It strengthens the plant tissue, increases the hardness and roughness of the surface, and thereby creates an additional barrier to water penetration and promotes water repellency.

The anatomical structure of straw, especially sclerenchyma cells, limits capillary absorption of water, unlike the soft cells of other plants. Sclerenchyma is a plant tissue consisting of densely packed cells with thickened, woody membranes that give plant organs strength. The membranes of sclerenchyma cells have high strength, close to that of steel[24].

Fig. 3.10 – Water droplets on the waxy cuticle of kale leaves

The main methods for reducing the hydrophobicity of straw include:

Alkaline treatment – destroys lignin and waxes[21]

Steam explosion treatment – opens cell walls[25]

Biological treatment using fungi – decomposes lignin[26]

Mechanical and thermal processing (extrusion, granulation)[27].

The general conclusion can be that without the use of thermal, biological or chemical pre-treatment methods, ensuring a sufficient level of reduction in the hydrophobic properties of straw is a difficult task.

C:N ratio

The C:N ratio is one of the key indicators characterizing the suitability of the feedstock for effective anaerobic digestion. The recommended carbon-to-nitrogen ratio for anaerobic digestion is typically in the range of 20:1 to 30:1[28, 29], with an optimum around 25–30:1[30]. This range ensures:

Sufficient carbon as an energy source for microbes,

Enough nitrogen for microbial protein synthesis,

Avoidance of ammonia inhibition (from excess N) or process slowdowns (from N deficiency).

Given that most types of crop residues have a C:N value >40 **(Table 3.4)**, there will be a need to balance their composition according to this indicator before anaerobic digestion. This will apply most to wheat straw and rapeseed straw.

Table 3.4 – Typical C:N values in crop residues

Crop Residue	C:N typical value	C:N range	Source
Wheat straw	80	60-100	31
Corn stalks	55	45-65	32
Sunflower stalks	50	40-60	33
Rapeseed straw	60	50-75	34
Soybean straw	30	25-35	35

The most effective and common method is co-fermentation with raw materials that are richer in nitrogen, such as pig manure, chicken manure, distillery stillage, etc. Below is an example of estimating the required proportion of granulated straw and poultry litter masses to achieve an acceptable C:N ratio in the mixture **(Table 3.5, Fig. 3.11)**.

Table 3.5 – Input characteristics of wheat straw pellets and poultry litter

Index	Unit	Value	
		Poultry litter	Wheat straw pellets
TS	% wet mass	30	91
VS	% TS	72	91
Nitrogen	g N / Kg VS	73.6	6
Carbon	g C / Kg VS	509	470
C:N	-	6.9	78.3

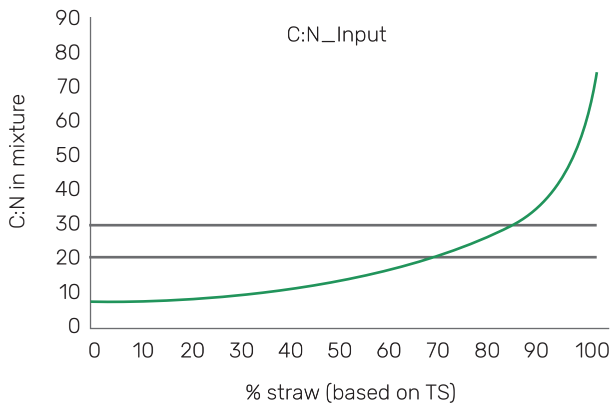


Fig. 3.11 – Dependence of C:N value on the proportion of straw pellets in a mixture with poultry litter

As can be seen from the results of the above example, to obtain a C:N value of 20-30, the ratio of straw pellets to poultry litter should be from 70%:30% (C:N=20) to 84%:16% (C:N=30) on a dry matter basis. In terms of fresh weight, this is from 43%:57% to 63%:37%, respectively.

Alternative strategies for optimizing the C:N value in crop residues can be the following:

Fungal pretreatment (selective biological delignification)

Water leaching or soaking

Controlled thermal pretreatment (low-temperature hydrothermal processing)

Alkaline pretreatment + solid/liquid separation

Adding artificial nitrogen fertilizer

White-rot fungi degrade lignin and some cellulose, which are carbon-rich, but they leave nitrogen, minerals, and proteins relatively untouched[26]. Thus, carbon is reduced via CO_2 evolution, but N, P, K stay in biomass or the resulting digestate.

Soaking straw in water removes soluble carbon compounds (e.g., simple sugars, phenolics) while retaining minerals like K, P, Mg that are less leachable under neutral pH[36]. To avoid excessive nutrient loss low temperatures and short durations should be applied.

Moderate heat (60-120°C) can release volatile carbon compounds (e.g., CO_2, acetic acid) but preserve structural N, P, and other elements[37] Thus, partial decarbonization with limited nutrient damage can be gained. At higher temperatures (>150 °C), nutrient volatilization or structural breakdown may occur.

NaOH or lime treatment solubilizes lignin and hemicellulose (carbon-rich), followed by pressing or filtration[38]. Nutrients may stay in the solid or liquid phase depending on solubility. Reaction time and pH value need to be adjusted to retain N, P in the solid phase if desired.

The use of artificial nitrogen fertilizers could be justified, since they will be applied with digestate in almost their entire absolute mass to the fields where they would be anyway applied for the cultivation of main crops. However, this approach should be carefully recognized in terms of the specific formula for different fertilizers and biological availability of nitrogen sources.

All of the listed alternative strategies have not yet been used on an industrial scale in the preparation of lignocellulosic raw materials for anaerobic digestion, so the feasibility of their use requires more detailed study and relevant research.

Bioavailability of organic matter

It is known that in the process of anaerobic digestion, lignin practically does not decompose or the duration of such decomposition significantly exceeds the economically feasible duration of fermentation. Therefore, the proportion of lignin in straw is a proportion of non-fermentable organic matter. In crop residues, the proportion of lignin is from 12-16% (soybean straw) to 18-22% (sunflower stalks, rapeseed straw) **(Table 3.6).**

Table 3.6 – Ligno-cellulose composition of crop residues

Residue Type	CEL (%)		HCEL (%)		LGN (%)		Source
	Aver	Range	Aver	Range	Aver	Range	
Wheat straw	37	32-42	24	20-28	18	15-21	39
Corn stalks	39	34-45	26	22-30	15	12-18	40
Sunflower stalks	36	30-42	24	20-28	18	15-22	41
Rapeseed straw	35	30-40	22	18-26	21	18-24	42
Soybean straw	37	32-42	23	20-26	17	14-20	40

In addition to lignin, part of the cellulose and hemicellulose, as well as part of the protein, are not fermented. The overall degree of decomposition of organic matter in straw during anaerobic digestion, as a rule, does not exceed 45-55%, and only when using alkaline treatment or steam-explosion technology it can reach 70-75%[21, 43]. Granulation of straw also leads to an increase in the degree of bioavailability of the organic matter of straw. For example, in the work[44] it was shown that the degree of conversion of dry organic matter of granulated wheat straw was 62.6%, which is 22.3% higher than that for unprocessed straw and 15.9% higher than that for straw crushed to a fraction of less than 2 mm.

Moisture content

The initial moisture content of the raw material in the biogas production process is a factor that, in particular, determines the possibility or feasibility of using certain technologies and types of bioreactors. Crop residues are, as a rule, dry biomass with a moisture content of 10-28% **(Table 3.7),** which, when using the most common agricultural anaerobic digesters of a "wet" type, will require providing a sufficient amount of moisture

.

Table 3.7 – Typical values of dry matter content in crop residues

Crop Residue	TS (%) typical (average) value	TS (%) range	Source
Wheat straw	86	84-92	45
Corn stalks	78	72-84	46
Sunflower stalks	80	76-85 (after field curing)	47, 48
Rapeseed straw	85	80-90	34
Soybean straw	86	82-88	49

The most obvious solution in this context may be the use of fresh water. For example, in order to organize the process of fermentation of straw in a "wet" type bioreactor with its initial moisture content of 15% and provided that the dry matter content in the reactor is not higher than 10%, it will be necessary to add at least 3.1 m^3 of water for each ton of straw. For a project with a capacity of 5 million Nm^3CH_4 per year, this would require the supply of at least 74.6 thousand m^3/year of water, which corresponds to the average water consumption of 1,550 residents in a city. However, in certain regions, especially given climate change, significant water shortages may be observed in certain periods of the year, which will limit the use of such a solution.

Another possible solution may be the use of recycling of the liquid fraction of the digestate into the process. However, such a solution will also have its limitations in terms of the share of such recycling, which is due to the risk of excessive increase in the concentration of salts and other substances undesirable for the fermentation process.

The most acceptable solution may be the co-digestion of dry biomass of crop residues with substrates that contain a sufficient amount of moisture and can be complementary to optimize the macro- and microelement composition of the mixture. One of the most suitable types of raw materials in this regard is liquid pig manure, which, as a rule, contains 94-98% moisture. In order to organize the process of fermentation of straw in a "wet" type bioreactor with its initial moisture content of 15% and provided that the dry matter content in the reactor is not higher than 10%, it will be necessary to add at least 3.9 m^3 of manure with a moisture content of 96% for each ton of straw. For a project with a capacity of 5 million Nm^3CH_4 per year, this would require the supply of at least 77.5 thousand m^3/year of manure, which corresponds to a pig farm with an average livestock of 15,700 heads.

As will be shown in **Section 6**, crop residue digestion is also possible in "dry" type fermenters. In this case, the need for water addition is significantly reduced, and the low moisture content of crop residues is not critical for the anaerobic digestion process.

Biochemical methane potential

The specific CH_4 output from crop residues per 1 Kg VS is noticeably lower than for the green biomass of the corresponding plants, which is due to the lignification of the biomass when it loses moisture. For example, from corn stover you can get up to 270-300 ml $CH_4 \cdot g^{-1}$ VS, in contrast to corn silage with a yield of 350-360 ml CH_4/g VS.

Methane yield from **wheat straw** ranges from 240 to 296 ml $CH_4 \cdot g^{-1}$ VS, with the highest yields achieved through co-digestion and digestate liquor recycling[50]. According to laboratory data of SEC Biomass, the methane yield from wheat straw pellets is 300-320 ml $CH_4 \cdot g^{-1}$ VS, which is 13-16% higher than for mechanically crushed straw 265-275 ml $CH_4 \cdot g^{-1}$VS. Similar results were also obtained in the work[27], where the methane production yields ranged from 260–319 L $CH_4 \cdot Kg^{-1}$ VS for the straw pellets and 262-289 L $CH_4 \cdot Kg^{-1}$ VS for the unpelletized straw.

Untreated **corn stalks** yield 256 ± 15 ml $CH_4 \cdot g^{-1}$ VS[51]. With alkaline pretreatment methane yield increased by 43.3% to 367 ± 35 ml $CH_4 \cdot g^{-1}$VS. According to laboratory data of SEC Biomass, crushed corn stalks can yield 306-317 ml $CH_4 \cdot g^{-1}$VS. In one experiment corn stover pellets yielded 247-257 ml $CH_4 \cdot g^{-1}$ VS, in another – 300 ml $CH_4 \cdot g^{-1}$VS. It is obvious that the variety of corn[52] and the corn harvest period can significantly affect methane output.

The biochemical methane potential of untreated **sunflower heads** is 210 ± 1.97 ml $CH_4 \cdot g^{-1}$ VS, and 127.98 ± 5.19 ml $CH_4 \cdot g^{-1}$ VS for untreated **sunflower stalks**. Heads are considered to be a better raw material for biogas production in comparison with sunflower stalks. After alkali pre-treatment, the yield of methane from sunflower head residues was 268.35 ± 0.11 ml $CH_4 \cdot g^{-1}$ VS, while the yield of methane from the treated sunflower stalks was 168.17 ± 6.87 ml $CH_4 \cdot g^{-1}$ VS[53].

A study [54] found that untreated **rapeseed straw** produced an average of 255.2 ± 7.7 ml $CH_4 \cdot g^{-1}$ VS of methane. Pulsed electric field (PEF) pretreatment increased methane production in rapeseed straw, reaching 290.8 ± 12.1 ml $CH_4 \cdot g^{-1}$ VS, which was a 14% increase compared to the untreated sample. Research by SEC Biomass has shown that untreated rapeseed straw can yield 170-200 ml $CH_4 \cdot g^{-1}$ VS, while mechanically crushed to a fraction of < 2 mm yields 226 ml $CH_4 \cdot g^{-1}$ VS, which is 13-33% more. Granulating rapeseed straw allows for an even higher methane yield of 256 ml $CH_4 \cdot g^{-1}$VS.

Soybean straw has relatively less potential compared to other types of crop residues. Untreated soybean straw can produce around 127±2 ml $CH_4 \cdot g^{-1}$ VS[55]. Pretreatment methods, such as NaOH-H_2O_2 and extrusion, can increase methane production by 28% to 62% compared to untreated straw. NaOH-H_2O_2 pretreatment, in particular, can increase methane production to 206 ± 2 ml $\cdot g^{-1}$ VS. Similar results, 145 ml $CH_4 \cdot g^{-1}$ VS, were obtained by SEC Biomass from soybean straw crushed to a fraction of < 2 mm. Granulation of soybean straw allowed to increase the yield of CH_4 by 22% to 177 ml $CH_4 \cdot g^{-1}$ VS, which, however, is a much lower indicator than for granulated wheat or corn stover.

Therefore, it can be summarized that different crop residues from different crops give different methane yields per unit of organic matter. At the same time, different methods of pre-treatment of crop residues are able to increase the yield of biogas to different degrees. Production of pellets from crop residues allows to increase the yield of methane by 10-20%, compared to untreated biomass. Among the main types of crop residues in Ukraine, the highest methane yields can be obtained from wheat straw and corn stalks, the lowest – from soybean straw and sunflower stalks.

Technologies of collection, transportation and storage of crop residues

SECTION 4

Crop residues form primary agricultural biomass (straw, corn stalks and cobs, sunflower stalks and heads, etc.), which is suitable for harvesting and has the greatest available potential of biomass of agricultural origin available for energy use in Ukraine. Such biomass is dispersed over the area of fields and therefore requires additional costs for harvesting, unlike secondary biomass, which is obtained during the processing of primary agricultural products (cake, husk, shell, shives, etc.).

The volumes of crop residues significantly depend on the varietal characteristics of agricultural crops, such as their yield, stem height and ratio of vegetative mass to grain, as well as on the soil and climatic conditions of the growing region, including the amount of precipitation, temperature regime and soil fertility, and, finally, on the applied agro-technology, in particular the tillage system, fertiliser application and harvesting methods. Existing harvesting technologies allow for partial collection of only the above-ground part of the crop, which is considered a by-product of crop production, for example, straw and chaff, which are usually collected from 2 to 5 t/ha[56]. At the same time, the stubble and underground part of the plant remain in the field. Crop by-products are characterized by low bulk density (for example, straw in uncompacted form has 20-50 Kg/m^3), therefore, to ensure effective logistics, it is advisable to press such biomass into square bales (round bales) with a density of 90-230 Kg/m^3, briquettes or pellets with a bulk weight of 650-700 Kg/m^3. It should be noted that there are situations when plant residues are collected in crushed form due to the impossibility and inexpediency of their compaction, in particular, due to high humidity. In addition, excessive moisture content in crop by-products causes biomass spoilage during storage. Controlling biomass moisture is especially important for autumn harvesting of plant residues, when rainy and cold weather is observed. In particular, such conditions arise when harvesting corn stover in October-November. Microbial activity slows down if the moisture content in the biomass is less than 22% and becomes almost inactive at a moisture content of less than 18%[57].

These and other features of crop residues should be taken into account when planning and organizing the supply chain. Anaerobic digestion of crop residues is a key element of the closed-loop economy in the agricultural sector. This process allows you to convert crop by-products into two valuable products: biogas (or biomethane) for the production of clean energy and digestate, an ecological organic fertiliser. The introduction of digestate back into the fields ensures the return of key nutrients to the soil, which reduces dependence on mineral fertilisers. Thus, the cycle that begins with the effective collection of crop residues ends with the generation of energy and the maintenance of soil fertility.

Harvesting is the most crucial period in the technology of growing agricultural crops. The main requirement for this event is to collect the entire biological crop yield without loss and preserve its food and feed qualities with minimal labour and financial costs, which can be achieved by clear planning and high organisation of harvesting operations.

The general strategy for organising the harvesting of grain and industrial crops is to be able to quickly and fully remove grain and seeds from the field, to avoid their spoilage and losses from shedding or the action of precipitation. Therefore, during the harvest, agricultural producers, faced with resource limitations, lack of time, adverse weather conditions, etc., pay primary attention to harvesting the main product with a minimum level of its quantitative and qualitative losses. The experience of farmers shows that to ensure the harvesting of specified volumes and the required quality of straw and corn stover, it is necessary to use special mechanised harvesting units equipped with equipment and qualified personnel. It should be noted that agricultural producers in the livestock sector have equipment for harvesting straw, but they harvest it for their own needs. Agricultural enterprises in the crop sector are ready to sell straw, but they lack the necessary equipment, in particular balers and loaders. Soil with untreated stubble quickly loses moisture, and weeds also grow. Therefore, by-products, in particular straw, must be removed from the fields simultaneously with the harvest. The terms of harvesting and removal of crop by-products from the fields must be agreed upon with farmers and strictly adhered to. In addition, special attention should be paid to the preparation of warehouses that must provide the appropriate conditions for storing biomass. It is also important to establish control and monitoring of the quality and quantity of supplied raw materials.

The need to use specialised machinery and equipment for the collection, processing and logistics of crop by-products leads to significant capital costs. Examples of such equipment are large square balers, self-loading trailers, powerful tractors, loaders, vehicles, crushers, briquetting presses, granulators, etc. This equipment must be maximally loaded, which requires careful planning taking into account the seasonality of agricultural activity, dependence on weather conditions and agro-technological limitations. Schemes of the main technologies for mechanized harvesting of crop by-products are shown in **Fig. 4.1**.

Currently, the most common way to harvest straw and other dry plant residues is baling directly in the field. Balers are used to form straw bales and tie them, allowing to obtain dense, square or round bales of a given shape and the required size. The following types of balers are distinguished: piston

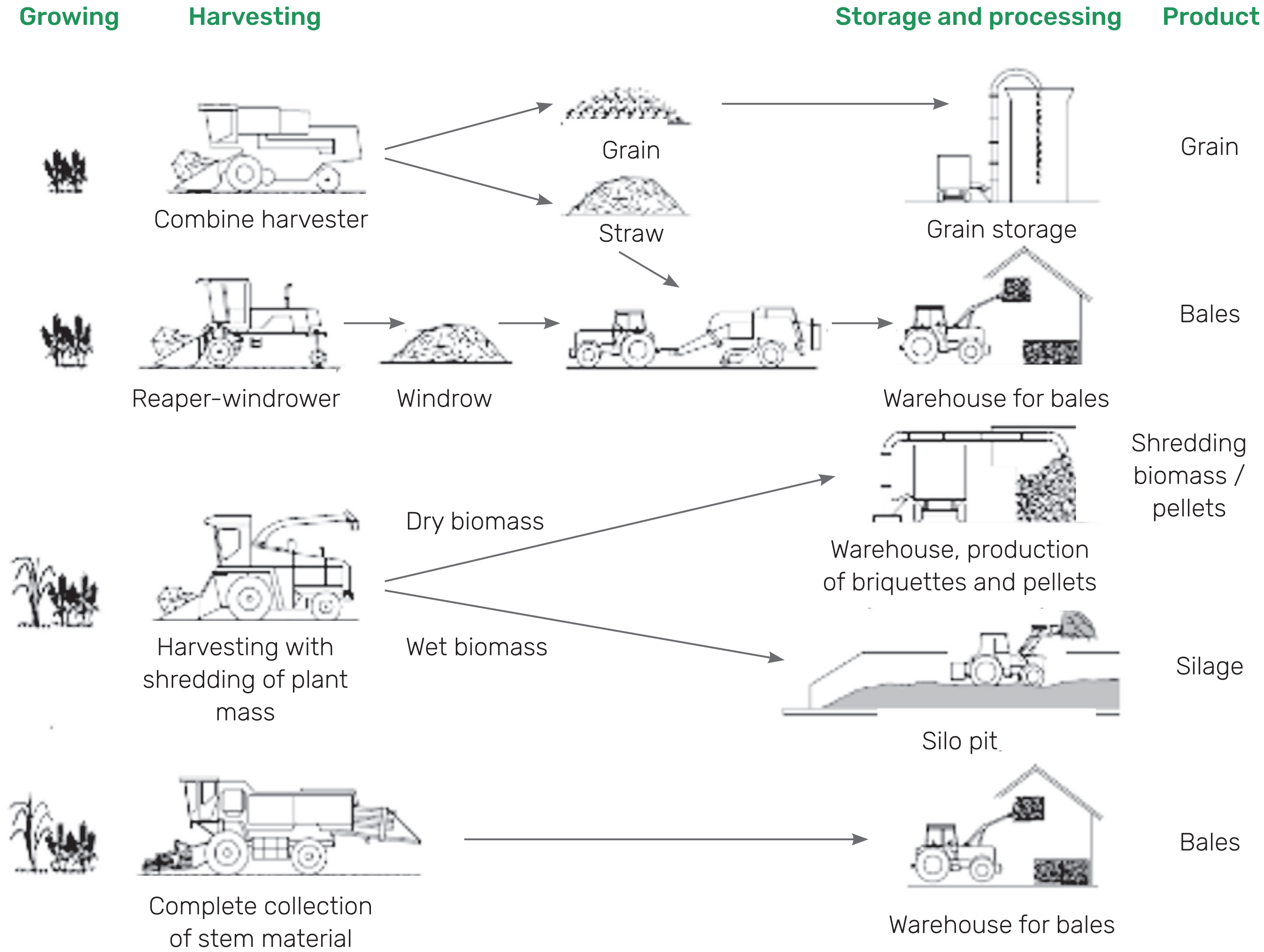


Fig. 4.1 – Options for harvesting the main products and crop residues[58]

Table 4.1 – Properties of straw bales[59]

Bale type	Dimensions L × W × H, cm	Weight, Kg	Density, Kg/m 3
Small square bales	70-90 × 46 × 36	12-15	90-100
Round bales	120 × 170*	220-270	100-120
Medium square bales	200-240 × 80 × 80	200-250	110-150
Mini-large square bales	230-250 × 120 × 70	290-450	150-215
Medium-large square bales	230-250 × 120 × 90	450-650	160-230
Large square bales	230-250 × 120 × 130	450-650	140-170
*Note: * width × diameter*			

balers for forming small, medium and large square bales, round balers with a constant and variable pressing chamber. Typical bale sizes and weights are given in **Table 4.1.**

Baler operating speed in the field:

> *small square bales 4-10 km/hour, typical 6.5 km/hour;*
>
> *large and medium square bales 6.5-13 km/hour, typical 8 km/hour;*
>
> *round bales 5-13 km/hour; typical 8 km/hour.*

However, it should be noted that round balers stop to unload bales, while square balers unload bales on the move. Therefore, the approximate efficiency of a square baler in the field is 80%, and that of a round baler is 55-65%.

In agriculture, in recent decades, the technology of harvesting hay and straw in round bales has become widespread, in particular in small farms. This is explained by the simplicity of the design of round balers and, accordingly, their lower cost compared to large square balers. Small square balers are also widespread in Ukraine. Round and small square balers are much cheaper than medium and large square balers. However, given the lower density of straw in round and small bales, lower pressing productivity, difficulties in logistics and bale storage due to poorer use of transport and warehouses at powerful bioenergy facilities, their use is limited. Also, medium-sized balers are rarely used for the production of bales for energy use due to higher costs for harvesting and loading operations. The possibilities of hay and straw harvesting technology using large square balers have expanded significantly in recent years, in particular, they can be used to harvest post-harvest corn residues – corn stover. These machines have undeniable advantages over other machine designs. The main ones are the following:

> *high productivity and correspondingly lower labour costs, in particular, one large square baler can collect biomass from the same area as 2-3 round balers;*
>
> *high pressing density, which in large square bales is over 25% higher than in round bales;*
>
> *maintaining high-quality raw materials;*
>
> *better use of vehicle carrying capacity, warehouse capacity, and increased loader productivity.*

When choosing a baler, the main factor that affects the entire chain of harvesting –transportation – storage – use of straw is often the size of the bale. Large square bales have different dimensions: width 1.2 m, height from 0.7 to 1.3 m, length from 2.0 to 3.2 m. The density of the bales depends on the type of raw material, the density of the windrows, the pressing speed and the design features of the baler and can be 120-300 kg/m^3 (for straw 230 kg/m^3).

Due to the significant compaction of the raw material, large square balers open up new opportunities for the use of straw and turn it into a promising commercial product not only for agricultural production, but also for bioenergy and various industries. At the same time, medium-large bales weighing 450-650 kg with a cross-section of 1.2 × 0.9 m and large bales of 450-650 kg – 1.2 ×1.3 m are most often used, which makes their transportation, loading and storage the most economically feasible.

In Ukraine, the most promising types of crop residues for biogas and biomethane production, given their volumes, are straw, corn stover and sunflower stalks. At the same time, domestic farmers have well developed the technology of straw harvesting, while corn by-products are harvested in limited volumes, although large-scale harvesting of corn stover is common in the USA, and sunflower stalks are not yet harvested. It will be made a feasibility study of harvesting straw and corn cobs in large square bales for further biomethane production in domestic conditions. For this purpose, we will consider a conventional farm with a total sown area of 10 thousand hectares, including 2,400 hectares designated for wheat straw harvesting and 1,900 hectares for corn stover harvesting.

Cost estimation for harvesting wheat straw in large square bales

Under good weather conditions during harvest, straw can be baled immediately after the combine has formed the windrows in the field. A typical agrobiomass supply chain consists of the following main technological operations: forming straw windrows by a combine harvester, baling, collecting bales and temporary storage near the field, loading and transporting straw bales to the main warehouse. Based on the type of bales, local conditions and available equipment, agricultural producers make some changes to this chain. In particular, loaders should be used to unload vehicles and stack large bales and round bales brought into the warehouse. The number of loading and transport operations depends on the approaches to organising storage. Additional operations may also occur after stacking straw in the windrow. If the straw is too wet (typical average moisture content above 15%), it should be given time to dry in the windrow before baling. If there is heavy rain, it may be necessary to use a rake once or several times. Modern rakes are designed to either distribute straw in a swath across the entire width of the rake (for air drying), or to collect/turn straw in windrows.

The most widespread method for large volumes of straw over 5 thousand tons/year is harvesting in large square bales **(Fig. 4.2)**, which involves forming straw windrows with a combine harvester (item 0), taking biomass from the windrows and pressing it into bales (item 1), collecting bales in the field with a tractor with a self-loading trailer and stacking bales in stacks (item 2), temporary storage of bales at a local warehouse near the field (item 3), loading bales with a loader onto vehicles (item 4), transporting bales to a central warehouse for main storage (item 5), unloading and storing bales (item 6), and long-term storage of bales (item 7).

The described scheme can be simplified if the bales are collected by a loader and loaded into vehicles directly in the field, thus, the technological operations of items 2 and 3 are not carried out. However, in this case, there is a need to use an additional loader in the field, which will collect the bales and stack them next to each other in separate groups for faster loading of the transport that must move across the field. Given this, the loading time will be longer than when using a tractor with a self-loading trailer. In addition, in rainy weather, the soil in the fields will get wet, which will hinder the movement of vehicles. Thus, there will be delays in removing the bales, and they will absorb moisture from precipitation not only from above, but from below, from the ground. Therefore, for harvesting straw in the fall, in particular, soybean straw, it is advisable to use self-loading trailers for quick removal of bales from the fields and temporary warehouses for storing biomass near the fields. It is better to choose the location of temporary storage areas near roads and on elevations for water drainage during rainfall.

Let's determine the cost of harvesting 4.0 t/ha of wheat straw with a base moisture content of 15% in large square bales from an area of 2400 ha, including its transportation by road from the field to a central warehouse over a distance of 20 km. The total volume of straw will be 9,600 t. A baling productivity of 6.0 ha/hour is assumed, which will allow for the collection and compaction of straw into bales from the base area in 400 hours. Considering an expected baling duration of 10 hours/day, it is advisable to use two balers. The list of technical equipment for straw harvesting from this area, according to the scheme described above, includes:

> *2 tractors with large square balers;*
>
> *1 tractor with a self-loading bale trailer;*
>
> *4 telescopic handlers;*
>
> *6 trucks with flatbed semi-trailers.*
>
> *The total cost of this equipment is 2,032 thousand EUR.*

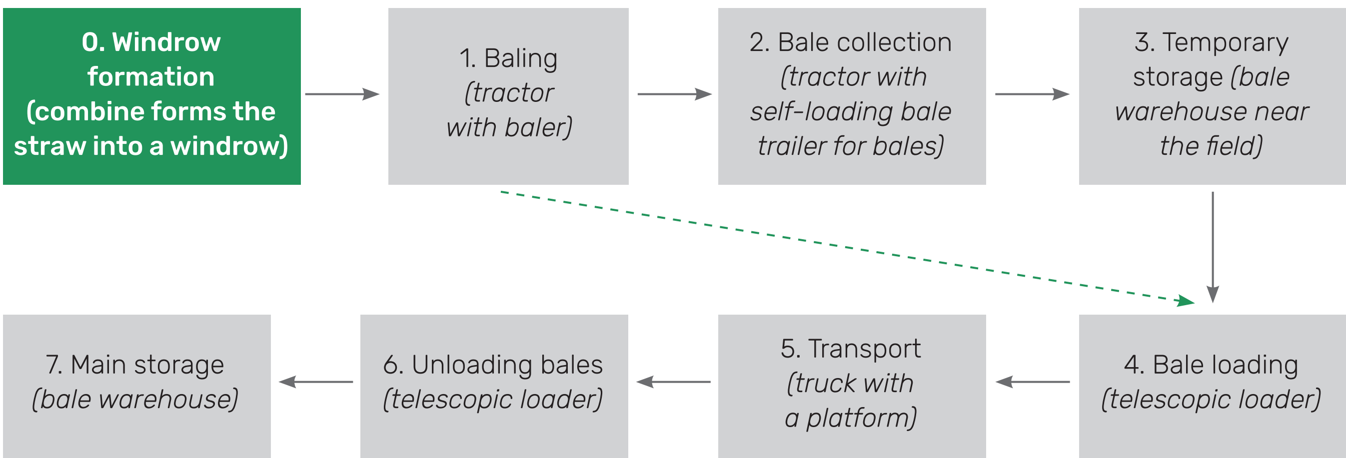


Fig. 4.2 – Structural diagram of straw harvesting in large square bales

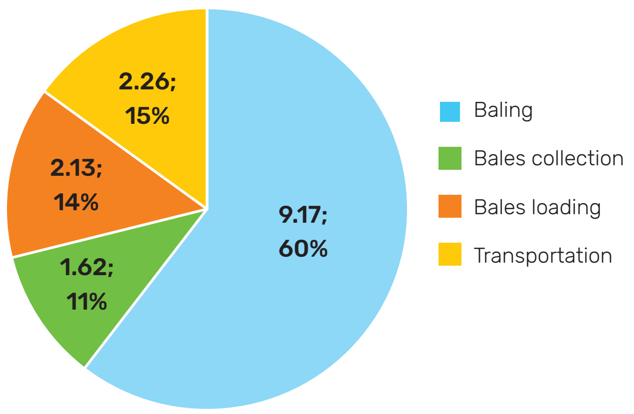


Fig. 4.3 – Cost structure for harvesting wheat straw with a moisture content of 15% in large square bales by technological operations, EUR/t

A base annual workload of 1,600 hours/year is adopted for tractors and handlers, and 1,840 hours for trucks. It is taken into account that the baler and self-loading bale trailer will be engaged in straw harvesting for 50% of their annual workload, tractors for 25%, telescopic handlers for 20%, truck tractors for 16%, and flatbed semi-trailers for 50%. For the remaining time, the machinery will be used for other purposes, including corn stover harvesting. The conditional cost of the equipment, taking into account the load for straw harvesting, is 594.6 thousand EUR. The results of calculations of costs for wheat straw harvesting and other assumptions are presented in **Table 4.2** and **Fig. 4.3**.

For a payback period of up to 7 years, depending on the load at the straw harvest, the selling price of large square straw bales with delivery to storage locations at the central warehouse is 25 EUR/t excluding VAT.

Cost estimation for harvesting corn by-products for grain in large square bales

Corn harvesting begins when the grain is fully ripe, at which point the supply of nutrients stops, and the grain moisture content is up to 35%. The moisture content of individual parts of the post-harvest residues is heterogeneous. The stems of corn cobs are always wetter (W=35-45%) than the grain (W=22-35%), but during drying, they evaporate moisture more intensively. Corn in the morning is wetter than in the afternoon by up to 7%. Immediately

Table 4.2 – Specific production costs for harvesting 9,600 tons of wheat straw with a moisture content of 15% from an area of 2,400 hectares

#	Cost item	Costs, UAH/t	Costs, EUR/t	Share, %	Note
1	Labor	49.5	1.05	6.4	160 UAH/hour, 7 operators on tractors and loaders; 6 drivers
2	Fuel and lubricant	181.2	3.83	23.5	Diesel fuel: 3.6 L per tonne of straw. Lubricants 15% of the diesel fuel cost
3	Maintenance and repair	147.0	3.11	19.1	Deduction of 5% from the cost of equipment, including loading
4	Materials	98.6	2.08	12.8	Twine 123 UAH/kg excluding VAT
5	Equipment depreciation	293.9	6.21	38.2	10 years, taking into account the conditional load of the equipment
	Total:	770.1	16.28		
	Production cost per ton of baled straw without depreciation	476.2	10.07		At the central warehouse

Notes: exchange rate 47.31 UAH/EUR

after harvesting, the moisture content of the stalks is within 45-60%. As a rule, it is believed that the moisture content of the stalks is 2 times higher than the moisture content of the grain. However, proper technology, which creates conditions for blowing biomass by the wind, allows it to be reduced to 30% in the field within 10 hours. Also, the moisture content of corn stover depends very much on the time of harvesting and weather conditions, and therefore, heavy rainfall during the harvest period will prevent the harvesting of biomass. During the harvesting campaign, when the moisture content of the corn grain falls below 20%, the moisture content of the corn stover decreases rapidly **(Fig. 4.4).** However, after the physical maturity of the corn grain, the dry matter yield of the corn stover decreases at an approximate rate of 1.6 centner/ha per week. Therefore, windrow formation and harvesting of the corn stover should be carried out as soon as possible after the corn grain is harvested.

Considering that the harvest will take place in the second half of autumn, when rainy and cold weather is observed, it is difficult to predict what the moisture content of the corn stover will be.

Therefore, it is advisable to define two strategies for harvesting and storing corn stover:

A. Dry biomass supply chain – at moisture content up to 25%, corn stover can be baled into square or round bales and stored under flexible cover similar to the company's established straw storage practices. Balers must be designed to handle this type of material;

B. Wet biomass supply chain – with a moisture content of over 25%, corn stover is harvested in shredded form and ensiled.

For harvesting wet corn stover, the widely used technology of harvesting corn silage based on a self-propelled forage harvester can be used. Therefore, let's consider the technology of harvesting corn stover for option A – a supply chain of dry biomass in large square bales.

The main difference between harvesting corn stover and straw is the need to use additional machines to form corn stover windrows **(Fig. 4.5)**. Since when harvesting corn for grain, only a small part of the stover passes through the combine,

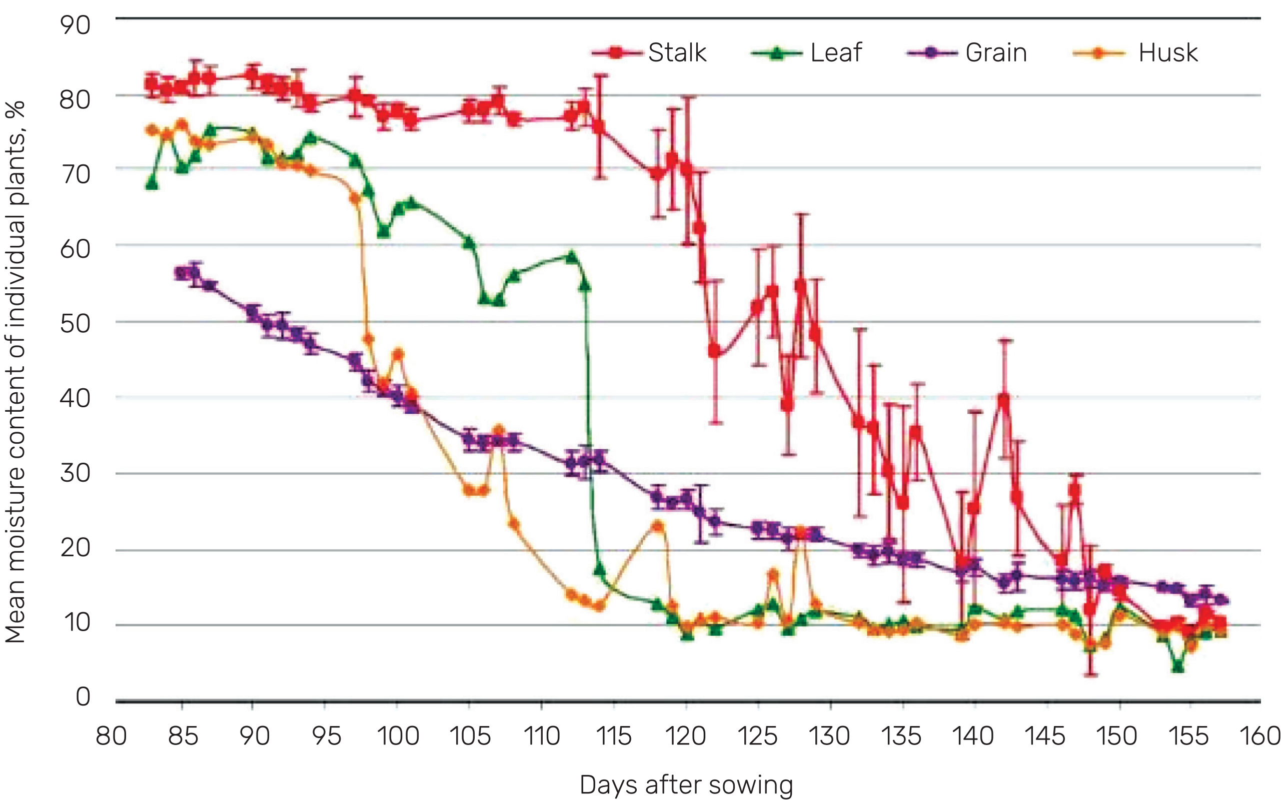


Fig. 4.4 – Moisture distribution in the aboveground biomass of standing corn[60]

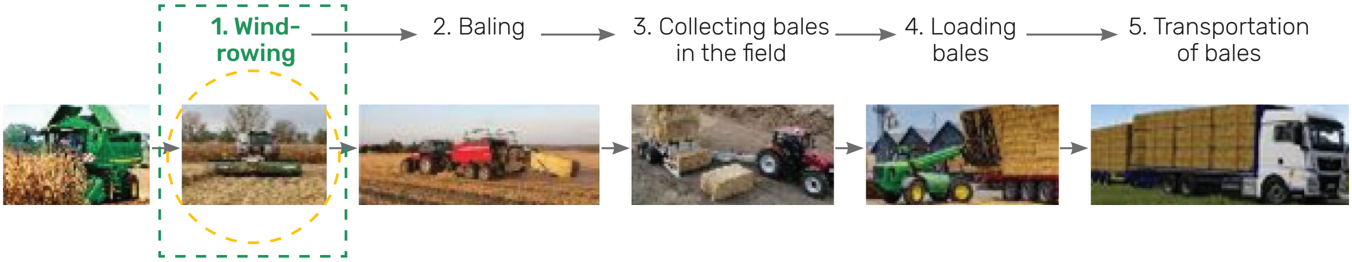


Fig. 4.5 – Technological scheme for harvesting corn cobs in large square bales

while the main part is scattered by the header and a conventional combine harvester cannot form windrows from biomass, it is proposed to use a stalk chopper windrower to form corn stover windrows. This machine picks up plant residues, cuts stalks, chops biomass and lays it in windrows. When harvesting straw, the combine harvester lays it in windrows and there is no need to use stalk chopper windrowers.

Fig. 4.6 shows the operation of the Berti LAND/P 600 BIOG model stalk chopper windrower with a working width of 6 m. Such a mulcher has a productivity of 2.5-4 ha/hour and is aggregated with a 220 hp tractor. The stalk chopper windrower can form one windrow in two passes with a width of 12 m, which will ensure more efficient use of the baler.

Next, the biomass from the windrows is picked up by a baler and baled into large square bales, and other technological operations fully correspond to the technological operations for straw harvesting. It is advisable to collect the bales with a special trailer and take them to a temporary warehouse near the field for more convenient loading of trucks. Then the bales are unloaded by a telescopic loader onto long platforms of semi-trailers, which will allow loading 30 bales, and transported to the central warehouse. Unloading of bales at the warehouse is also done by a telescopic loader. Given the short-term use, it is better to rent trucks.

Let's estimate the costs of harvesting 4.5 t/ha of corn stover with a base moisture content of 25% in large square bales from an area of 1,900 ha. This includes transportation by road from the field to a central warehouse over a distance of 20 km. The total volume of corn stover will be 8,550 t. A baling productivity of 5.0 ha/hour is assumed, which will enable the collection and compaction of corn stover into bales from the designated area within 380 hours. Given the limited timeframe of the harvesting campaign, it's advisable to use two balers. The list of technical equipment for harvesting corn stover from this area, following the scheme described above, includes:

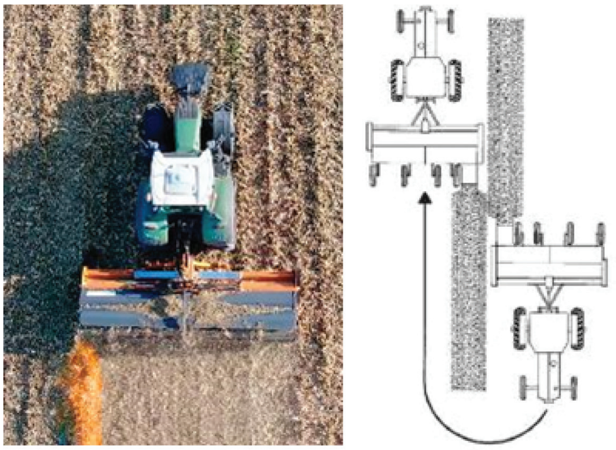


Fig. 4.6 – Operation of LAND/P 600 BIOG and scheme of doubling the windrows

- *3 tractors with stalk chopper windrowers;*
- *2 tractors with large square balers;*
- *1 tractor with a self-loading bale trailer;*
- *2 telescopic handlers;*
- *6 trucks with flatbed semi-trailers.*

The total cost of this equipment is 2,812 thousand EUR. Similar to straw harvesting, a base annual workload of 1,600 hours/year is adopted for tractors and handlers, and 1,840 hours for trucks. It is assumed that the baler and bale trailer will be engaged in corn stover harvesting for 50% of their annual workload. Tractors with stalk chopper windrowers will be utilized for 15%, other tractors for 25%, telescopic handlers for 20%, truck tractors for 10%, and flatbed semi-trailers for 50%. For the remaining time, the machinery will be used for other operations. The conditional cost of the equipment,

Table 4.3 – Specific production costs for harvesting 8,550 tons of corn stover with a moisture content of 25% from an area of 1,900 hectares

#	Cost item	Costs, UAH/t	Costs, EUR/t	Share, %	Note
1	Labor	54.0	1.14	4.5	160 UAH/hour, 10 mechanics on tractors and loaders and 6 drivers
2	Fuel and lubricant	278.5	5.89	23.3	Diesel fuel: 5.5 L per tonne of corn stover. Lubricants 15% of the diesel fuel cost
3	Maintenance and repair	260.2	5.50	21.8	Deduction of 5% from the cost of equipment, including loading
4	Materials	83.2	1.76	7.0	Twine 123 UAH/kg excluding VAT
5	Equipment depreciation	520.4	11.00	43.5	10 years, taking into account the conditional load of the equipment
	Total:	1196.3	25.29		
	Production cost per ton of baled straw without depreciation	675.9	14.29		At the central warehouse

taking into account the load for straw harvesting, is 940.5 thousand EUR. The results of the calculations of the costs for harvesting corn stover and other assumptions are presented in **Table 4.3** and **Fig. 4.7.**

For a payback period of up to 7 years, depending on the load during corn harvesting, the selling price of large square bales of corn stover with delivery to storage locations in the central warehouse is 35 EUR/t excluding VAT.

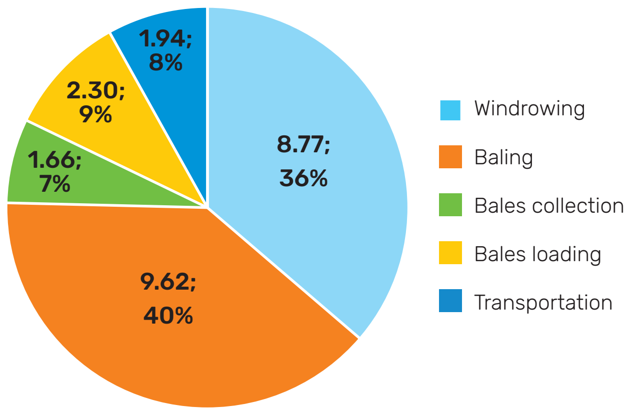


Fig. 4.7 – Cost structure for harvesting corn stover with a moisture content of 25% in large square bales, EUR/t

Technologies for pretreatment of crop residues before anaerobic digestion

SECTION 5

The pretreatment of lignocellulosic agro biomass is a crucial step of biogas production. Its goal is to break down the complex structure of lignocellulose to allow the access to cellulose and hemicellulose for active components, which will subsequently converted those polimers into simple sugar molecules through enzymatic or acid saccharification.

The tasks of pretreatment of lignocellulosic biomass before fermentation also include:

> *Increasing the specific surface area for mass transfer*
>
> *Reducing hydrophobicity*
>
> *Homogenization*

Various methods can also achieve side effects, such as changing the balance of individual components and chemical elements, reducing the total mass of organic matter, changing the bulk density.

Increasing the specific surface area for mass transfer is achieved by disintegration of fibers and opening the internal cell walls for penetration of moisture and microbes. As a rule, the first stage of disintegration of crop residues is their mechanical grinding. The combination of mechanical and thermal methods, such as the steam-explosion method or granulation, allows for additional disclosure of the fiber structure. Disintegration of fibers allows for significantly increasing the homogenization of straw particles in the reactor, while reducing the viscosity of the mixture and, accordingly, the consumption of electrical energy for the transfer and mixing of mixtures. This also reduces the tendency for the solid phase to stratify in technological tanks, and therefore complicate or block the operation of technological equipment. Increasing the mass exchange surface, and therefore the rate of conversion of organic matter into biogas, allows you to reduce the anaerobic digestion duration and, accordingly, the cost of bioreactors.

Reducing hydrophobicity is a more complex task, which, as a rule, is not solved only by mechanical disintegration of fibers. As shown in **Section 3**, reducing the hydrophobic properties of straw can be achieved by thermal, chemical and biological methods, or their combination, including with mechanical methods.

Methods and their effectiveness

Various pretreatment methods have been described in the literature, differing in effectiveness, cost, and terminal impact on the fermentation process. Recent advancements emphasize the importance of pretreatment integration in downstream processes, such as enzymatic hydrolysis and fermentation, to reduce costs and improve the overall efficiency[61].

Four main groups of pretreatment methods can be distinguished, namely: physical, chemical biological, and combined methods **(Fig. 5.1).**

Physical	• Mechanical • Thermal • Ultrasound • Electrochemical
Chemical	• Alcali • Acid • Oxidative
Biological	• Microbiological • Enzymatic
Combined processes	• Steam explosion • Extrusion • Thermochemical

Fig. 5.1 – Main pretreatment methods for lignocellulosic biomass

Physical methods

Mechanical grinding

Mechanical pretreatment is carried out by mills and either makes the pieces of substrate smaller or squeezes them in order to break open the cellular structure, increasing the specific surface area of the biomass [62]. This gives greater possibility for enzymatic attack, which is particularly important for lignocellulosic substrates. Particle size reduction not only increases the rate of enzymatic degradation, it can also reduce viscosity in digesters (thus making mixing easier) and reduce the floating layers issue. All particle size reduction is helpful, but a particle size of 1 to 2 mm has been recommended for effective hydrolysis of lignocellulose[63]. Mechanical pretreatment has a major disadvantage – mills can be damaged by inert substrate components, such as stones or pieces of metal, and equipment repairs can be very expensive. Thus, the rigorous methods for preliminary removal of mechanical impurities before grinding should be applied.

Mechanical grinding of straw is usually the first or main processing step before fermentation, regardless of the subsequent methods used. Lignocellulosic biomass is usually grinded in 2-3 stages, depending on the desired target size of particles. The particle size is usually 10-50 mm after the first stage (coarse grinding) and 0.2-2 mm after the final grinding[64]. The degree of grinding should be determined taking into account the ratio of energy input and the effect obtained.

For grinding lignocellulosic biomass, two-roll, knife and hammer grinders, ball, vibratory, colloid and disc mills, as well as extruders are used.

As a rule, the energy requirement for mechanical grinding depends on the type of grinder, the initial and target size of particles, as well as the characteristics of the biomass, in particular the moisture content of the biomass being processed. In turn, the type of grinder is chosen depending on the characteristics of the biomass and the planned technology for its processing. Colloid mills and extruders are only suitable for grinding wet materials with a moisture content of more than 15-20%, while two-roll, hammer or knife grinders are only suitable for grinding dry biomass with a moisture content of up to 10-15%. Ball or vibrating ball mills are universal types of disintegrators and can be used for both dry and wet materials.

Knife, hammer and screw grinders or their combinations are the most typical equipment used for grinding lignocellulosic raw materials. The design of the grinders is closely depends on the characteristics of the biomass, such as mechanical properties, its dimensions and moisture content.

The specific electrical energy consumption for grinding crop residues can be roughly estimated by the following equation[65]:

$$SED_{HM} = 4{,}3 \cdot MC \cdot D_p^{-0{,}8},$$

where SED_{HM} – specific electricity consumption, kWh/t of dry matter; MC – raw material moisture (on wet weight), %; D_p – target size of particles of raw material, mm.

The consumption of electricity for straw grinding can range 20-100 kWh/t, depending on the equipment used, straw properties and target size of particles. For example, a knife grinder consumes 30 kWh/t with a target particle size of 6 mm[66]. A hammer grinder consumes 2-5 times more than a knife one[67].

Heat pretreatment

In thermal pretreatment process the substrate is heated (typically 125 to 190 °C) under pressure and held at that temperature for up to one hour. In laboratory, this can be carried out with pressure cookers, autoclaves or microwave heaters. Dry substrates need additional water before thermal treatment. The presence of heat and water disrupts the hydrogen bonds that hold together crystalline cellulose and the lignocellulose complexes, causing the biomass to swell[68]. Thermal pretreatment is often carried out with chemicals or in combination with mechanical shearing.

Thermal (including thermochemical or thermomechanical) pretreatment only increases biogas yield up to a certain temperature, above which biogas production decreases[69, 70]. Therefore, the trick with all pretreatment involving high temperatures is to find the optimum conditions that break down the substrate. At very high temperatures, certain dark-coloured xylose and lignin breakdown products are formed. These compounds include heterocyclic and phenolic compounds (such as furfural)[57].

Chemical methods

Chemical treatment is carried out by adding an acid to the substrate, usually it can be sulphuric acid (acid hydrolysis), or an alkali, like sodium hydroxide (NaOH) or ammonia hydroxide (NH_4OH) (alkaline hydrolysis).

Acid hydrolysis is one of the oldest methods of lignocellulosic biomass pretreatment. It involves the use of concentrated or dilute acids to break down hemicellulose and cellulose into simple sugars. Sulfuric acid is used most commonly for that purpose. In the process, hemicellulose is converted into pentoses (xylose and arabinose), while cellulose is broken down into hexoses (glucose, mannose)[56]. The two main approaches used in acid hydrolysis are:

> *Concentrated acid hydrolysis. This process is carried out at low temperatures (around 50°C) but with a high acid concentration (70-90%). Despite its high saccharification efficiency, it requires costly acid neutralization and recovery, making the process less cost-effective than other methods.*
>
> *Dilute acid hydrolysis. The process is conducted at higher temperatures (140-200°C) with low acid concentrations (2-5%). This method is cheaper but less efficient than concentrated acid hydrolysis. It also generates significant amounts of by-products, that must be removed before fermentation.*

Chemical treatment requires time for chemical reactions to occur, typically from 1 hour to 2 days. Chemical reagents can lead to the formation of inhibitory by-products that reduce the efficiency of the methane production process, and sometimes even stop it completely. The use of H_2SO_4 involves hydrogen sulphide (H_2S) formation, which at certain concentrations becomes an inhibitor to the anaerobic process[71]. Besides, Na^+ at high concentrations is known to be an inhibitory ion for some methanogenic bacteria[72]. Before being submitted to anaerobic digestion, the prepared mass must be neutralized, which involves minimizing the residual acid and aligning the pH value closer to the neutral level.

The consumption of electrical energy in chemical methods of straw processing, which includes mixing and pumping, is quite high – 50-120 kWh/t. The cost of chemical reagents, taking into account the need for neutralization (pH compensation) before feeding for fermentation, and the need to comply with strict conditions of their use, limit the feasibility of these methods as straw pretreatments for fermentation. It is also worth considering the cost of the chemical treatment systems themselves, which require acid and alkali resistance.

New approaches focus on mitigating the formation of fermentation inhibitors by presoaking biomass in alkaline solutions before acid treatment, reducing the generation of furfural and hydroxymethylfurfural (HMF)[73]. Advances in reactor design and the use of acid-resistant materials have further improved the scalability and efficiency of acid hydrolysis systems. Additionally, integrating advanced biocatalysts into acid hydrolysis processes has been shown to enhance sugar recovery rates while minimizing by-product formation, as highlighted in recent research[74].

Various solvents can also be used to break down cellulose, such as Organosolv or the noeteric DES (Deep Eutectic Solvents)[75], as well as hydrogen peroxide H_2O_2.

Biological methods

Biological pretreatment methods involve the use of microorganisms, such as fungi and bacteria, that naturally decompose lignocellulose. This process is less aggressive than chemical or thermal methods, but it takes longer and requires optimal environmental conditions, such as moisture, temperature, and oxygen availability.

The advantages of biological methods are as follows:

> *Low energy demand compared to thermal or chemical pretreatment;*
>
> *Minimimum formation of fermentation inhibitors;*
>
> *These processes can be integrated with fermentation, shortening the biogas production time.*

The disadvantages of biological methods include the long decomposition time and the need to maintain specific conditions, which are difficult to achieve on an industrial scale. Additionally, the efficiency of lignin breakdown by microorganisms is limited, meaning that these methods are often used in combination with other pretreatment techniques.

Common methods of biological pretreatment include the use of 2-stage fermentation, with the first stage being hydrolysis. While the pH during methane production must be stabilised on the level between 6.5 and 8, the pH value hydrolyse reactor (the preacidification step) should be in between 4 and 6, which inhibits methane production and causes volatile fatty acids to accumulate. Microbiological pretreatment can speed up the degradation rate of substrates in AD. In general, cellulose-degrading, hemicellulose-degrading and starch-degrading enzymes work best between pH 4 and 6 at temperatures from 30 to 50°C, so the pre-acidification step increases the degradation rate by creating an optimal environment for these enzymes[57].

Enzymes that break down biomass are already present in anaerobic digesters as they are produced by the microorganisms of AD. To enhance this breakdown, a mixture of enzymes can be added, and may include cellulose-, hemicellulose-, pectin- and starch-degrading enzymes. Enzyme additives can be applied in three different ways: by direct addition to a single-stage anaerobic digester, by addition to the hydrolysis and acidification reactor (1st stage) of a two-stage system, or by addition to a dedicated enzymatic pretreatment reactor.

Many fungi, particularly white-rot fungi, are known for their ability to remove environmental pollutants from solid and liquid waste[76]. Although white-rot fungi can delignify substrates, they also remove some of the organic matter than could be used for anaerobic digestion.

Combined methods

Steam-explosive autohydrolysis

One of the well-known methods of processing lignocellulosic biomass is steam-explosive autohydrolysis. This method involves biomass being exposed to explosive decompression as a result of its subjectification to the high pressure of saturated steam and its sharp decrease. The steam explosion is initiated when the temperature reaches 160-260°C and the corresponding pressure is 10-30 bar. Typically, such conditions are achieved after the sample is kept for a time from a few seconds to a few minutes. Steam explosion at 180 °C requires ~190 kWh/t[77].

A sudden decrease of pressure to atmospheric level leads to degradation of hemicellulose and lignin conversion under the influence of high temperatures, thereby increased potential of cellulose hydrolysis[78]. The higher the pressure and temperature of biomass holding in the steam-explosion method, the more the lignocellulose structure is destroyed, but the formation of toxic compounds and inhibitors, such as furfural, 5-hydroxymethylfurfural (OMF), formic acid, levulinic acid, acetic acid, phenolic compounds, also increases[79].

The study[80] showed that after pre-treatment of wheat straw by the steam-explosion method (at temperatures of 160-200°C and a holding time of 0.16-0.33 h), the methane yield increased by a maximum of 20% – from 275.6 L CH_4• Kg^{-1} VS (for untreated straw) to 331 L CH_4• Kg^{-1} VS.

The advantages of thermo-pressure pretreatment:

> *It breaks down the lignocellulose structure without using additional chemicals, making it more environmentally friendly compared to other methods;*
>
> *Rapid decompression allows for quick and efficient sugar release;*
>
> *This pretreatment generates fewer toxic by-products, minimizing the need for further detoxification.*

Recent innovations, such as microwave-assisted thermo-pressure pretreatment, have demonstrated enhanced sugar recovery rates and lower energy consumption compared to conventional steam explosion[81]. Furthermore, the addition of alkaline catalysts during steam explosion has been shown to improve lignin removal, enhancing cellulose accessibility[82].

Extrusion and pelleting

In an industrial extruder, the material is fed into the extruder and conveyed by screw along a tube, where it is exposed to high pressure, temperature and shear forces. Biogas substrates in extruders are subjected to the same forces, causing tough fibres to break. The sudden drop in pressure as the substrate leaves the extruder might also help substrate breakdown.

Extrusion effectively breaks the cell structure of biomass which results in faster methane production, which in turn facilitates higher organic loading rates[83]. A major problem with extrusion pretreatment technology is the screws, which have to be changed after a few months due to abrasion. As with other mechanical pretreatment technologies, stones or metallic materials in the substrates severely reduce the life time of the screws. This has a negative impact on the economics of the extrusion process[57].

One of the commercially widespread extrusion technologies is the production of pellets and briquettes. Such technologies are also widely used for pelleting straw and corn stover. The optimal value of straw moisture content during granulation should not exceed 14%. As humidity increases, the productivity of the production line decreases, and the specific electricity consumption for production increases[84] **(Fig. 5.2).**

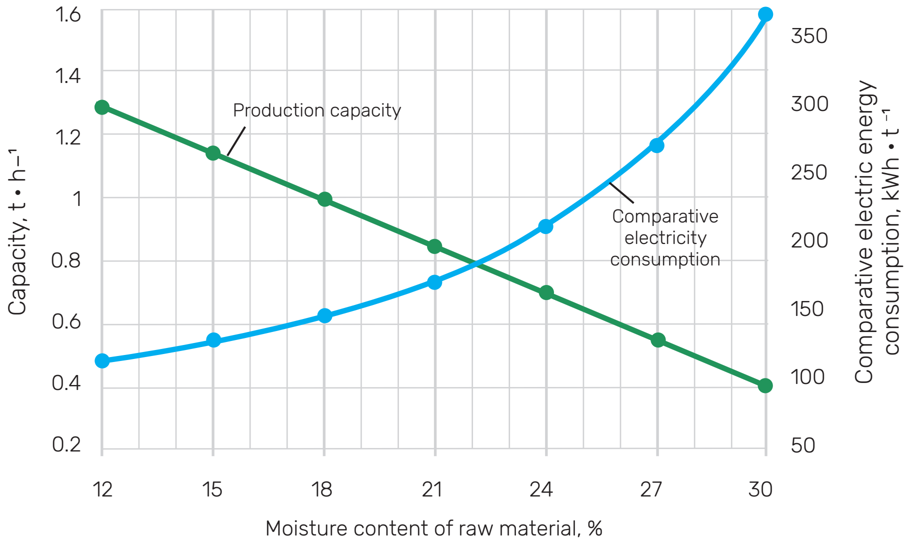


Fig. 5.2 – Dependence of productivity and electricity consumption in the production of pellets on the humidity of the raw material

Electricity consumption for processing crop residues into pellets significantly depends on the production productivity of the pelletizing line **(Table 5.1)**.

Table 5.1 shows that the total additional electricity costs for pelletizing, compared to only grinding with hammer grinders, are 64-109 kWh/t. Considering the fact that extrusion allows to increase the methane yield by at least 10-15%, which corresponds to 15-25 m^3CH_4/t, compared even with straw finely grinded by mechanical grinders, the additional energy of such methane of 156-234 kWh/t covers the power consumption for pelletizing. If we also take into account the reduction in electricity costs for mixing in bioreactors due to the reduction in viscosity and tendency to stratification of the mixture with pelletized straw, as well as the reduction in the duration of anaerobic digestion process, the energy effect of straw pelletizing is obvious.

Comparison of methods

It can be summarized that the considered methods of pretreatment of lignocellulosic raw materials generally allow to increase the specific mass exchange area and bioavailability of organic matter, but have different degrees of influence on different types of polysaccharides, such as cellulose, hemi-

Table 5.1 – Estimated electricity consumption for processing crop residues into pellets

Production processes, equipment	Nominal production capacity of the line, t/h			
	1	2	3	5
	Specific electricity consumption, kWh/t of pellets			
Primary grinding	20	18	18	16
Final grinding (hammer grinders)	45	41	39	37
Conditioning (preparation for granulation)	5	5	4	4
Granulation	76	56	47	38
Granules cooling	4	4	4	3
Conveyors, pneumatic transport	20	18	18	16
Lighting, control systems, other consumption	4	3	3	3
TOTAL	**174**	**146**	**133**	**118**

Table 5.2 – The influence of different pretreatment methods on the breakdown of lignocellulose[79]

Process	Cellulose decrystalisation	Hemicellulose degradation	Lignin degradation	Increasing specific surface
Biological				+
Milling	+			+
Steam explosion		+	+	+
Concentrated acid		+	+	+
Diluted acid		+		+
Alcali		-	+	+
Extrusion				+

A plus symbol (+) indicates that the pretreatment method has this effect, a minus symbol (-) indicates that it has no effect, and no symbol means it is unclear if there is an effect or not.

Table 5.3 – Advantages and disadvantages of different pretreatment technologies[79]

Process	Advantages	Disadvantages
Milling	• increases surface area • makes substrate easier to handle • often improves fluidity in digester	• increased energy demand • high maintenance costs / sensitive to stones etc.
Hot water (TDH)	• increases the enzyme accessibility	• high heat demand • only effective up to certain temperature
Alkali	• breaks down lignin	• high alkali concentration in digester • high cost of chemical
Microbial	• low energy consumption	• slow • no lignin breakdown
Enzymatic	• low energy consumption	• continuous addition required • high cost of enzymes
Steam explosion	• breaks down lignin and solubilises hemicellulose	• high heat and electricity demand • only effective up to certain temperature
Extrusion	• increases surface area	• increased energy demand • high maintenance costs / sensitive to stones etc.
Acid	• solubilises hemicellulose	• high cost of acid • corrosion problems • formation of inhibitors, particularly with heat

cellulose and lignin **(Table 5.2)**. Also, an important aspect of the influence is the possibility of the formation of by-products that can be inhibitors of the anaerobic fermentation process, which is inherent in the use of high-temperature or chemical methods. The advantages and disadvantages of various methods are given in **Table 5.3.**

Equipment

There is a number of commercially available solutions on the biogas plant equipment market that allow simultaneous straw pre-treatment and feeding into bioreactors, ensuring full integration into the biogas production. Some examples of such

Fig. 5.3 – Biogringer and its layout with a raw material feed system

equipment available in open sources or already presented in the Ukrainian market are given below. The provided examples present the different pre-treatment methods or their combinations. The list of equipment provided is not exhaustive among what is presented on the market and is not presented here as recommended for use exclusively.

Equipment based on the mechanical pretreatment methods

The MEBA BIOGAS GmbH **Biogrinder (Fig 5.3)** is designed in two sizes and several engine options, allowing for optimal integration with the biogas plant, taking into account the raw material.

The grinder works on the principle of a hammer mill, breaking the raw material into small particles. Centrifugal forces allow for effective mixing of different types of raw materials and grinding them against the ribbed walls of the crusher. For effective grinding, the raw material must be properly moistened and for this purpose a separate supply of the liquid phase to the dosing system can be provided. A typical solution from the company is to install the grinder directly on the frame of the raw material container. The container is equipped with a feeding, mixing and dosing system, which ensures uniform operation of the grinder and the supply of prepared raw materials to the reactor feed system.

Another example of grinding technology equipment is provided by engineering and manufacturing company BioG GmbH. The company is one of the few companies that is actively working in

a) b)

Fig. 5.4 – BIOCRUSHER equipment: a) equipment layout; b) crusher

the area of using agricultural residues for biogas production and offers its own developments in the field of harvesting corn stalks and their processing. For biogas plants, the company offers a ready-made comprehensive solution – **BIOCRUSHER**, which includes a raw material storage bunker with a mixing and dosing system, a crusher, and a finished raw material supply system **(Fig. 5.4 a).** For crushing mixed raw materials, the company offers LINDER and BHS equipment **(Fig. 5.4 b),** which are leaders in the world market in the field of crushing and sorting. The basic principle of operation is similar to MEBA equipment. Impact and shear forces optimally crush and grind the input material **(Fig. 5.5)**, which accelerates biogas formation and makes the overall process more stable.

The design and operating principle of both crushers are the same and differ in technical features. The advantage of such crushers is low sensitivity to the input raw materials, short residence time of particles in the crusher and high productivity. Due to the fact that the main energy is spent on crushing, and not on heating, this makes the process energy-efficient. The crusher drive power can be from 37 to 90 kW. The crusher design itself is made in such a way that it provides easy and quick access for maintenance and repair, and wide necks ensure easy feeding and unloading of raw materials.

The **Vogelsang PreMix system** allows you to mix several different streams of raw materials simultaneously, in particular liquid and solid fractions, and feed the mixture to the bioreactor **(Fig. 5.6)**. This solution is usually standard when using silage, so when using fibrous raw materials, in particular straw, the system is additionally equipped with shredding equipment. As a rule, shredders are installed at the inlet to the mixing and feeding system, but for additional shredding, RotaCut can be installed on the pressure pipelines. The level of shredding is regulated by the selection of grates and the speed of rotation of the self-sharpening knives.

For better mixing and crushing of solid particles, it is advisable to install a two-shaft X-Ripper at the inlet, which allows you to crush straw, wood, bones, vegetables and fruits, plastic and textiles. By adjusting the size of the knives and the gap between them, you can adjust the productivity of the installation and the degree of grinding of raw materials. The specially designed knives rotate at different speeds, which allows you to capture raw materials and self-clean.

The **straw milling plant** offered by **LinKa** in cooperation with Euromilling is essentially a mini-complex for specialized straw milling before feeding to anaerobic digestion **(Fig. 5.7).**

LinKa straw milling plant include all the necessary equipment enabling processing the baled straw of 10-20% DM into the desired particles size, namely:

> *Overhead travelling crane automatically removes strings from straw bales*
>
> *Straw bale shredder shreads straw bales for further processing*
>
> *Stone, metal and other foreign objects trap ensures unwanted contaminants are removed*
>
> *Pre-grinding mill prepares straw for fine grinding*
>
> *Fine grinding hammer mill achieves the desired straw particle size*
>
> *Premixer homogenizes straw for optimal biogas production*
>
> *Pump to reactor tank transfers straw powder to the reactor*
>
> *Control and monitoring system – supervises, optimizes, and safeguards operations, ensuring efficiency, safety, data acquisition, and remote management.*

Considering that straw in such equipment is crushed almost to a powdery state, the complex is manufactured in an explosion-proof design. The complex for processing 8 t/h of straw with a humidity of up to 20% has an installed electrical capacity of 510 kW_e and consumes 76 kWh/t of straw.

Equipment based on extrusion pretreatment methods

The **BIOEXTRUDER** technology and equipment were developed by LEHMANN company. The process of bioextrusion in double-screw extruders is based on hydrothermal desintegration and has proven it's worth for material and energy use of lignin containing substrates. The feedstock is chopped and desintegrated partly up into the cell structure **(Fig. 5.8)** by means of repeatedly

Corn stover | Manure with straw bedding | Straw | Grass

Fig. 5.5 – Some types of raw materials before and after crushing in BIOCRUSHER equipment

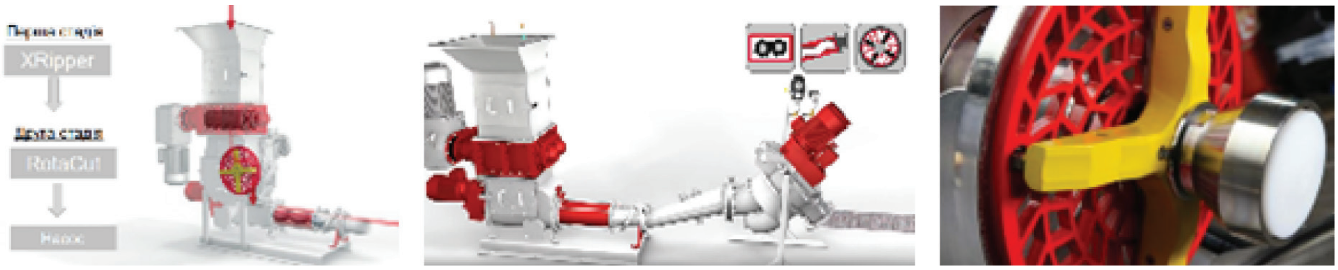


Fig. 5.6 – PreMix system with additional X-Ripper and RotaCut shredders

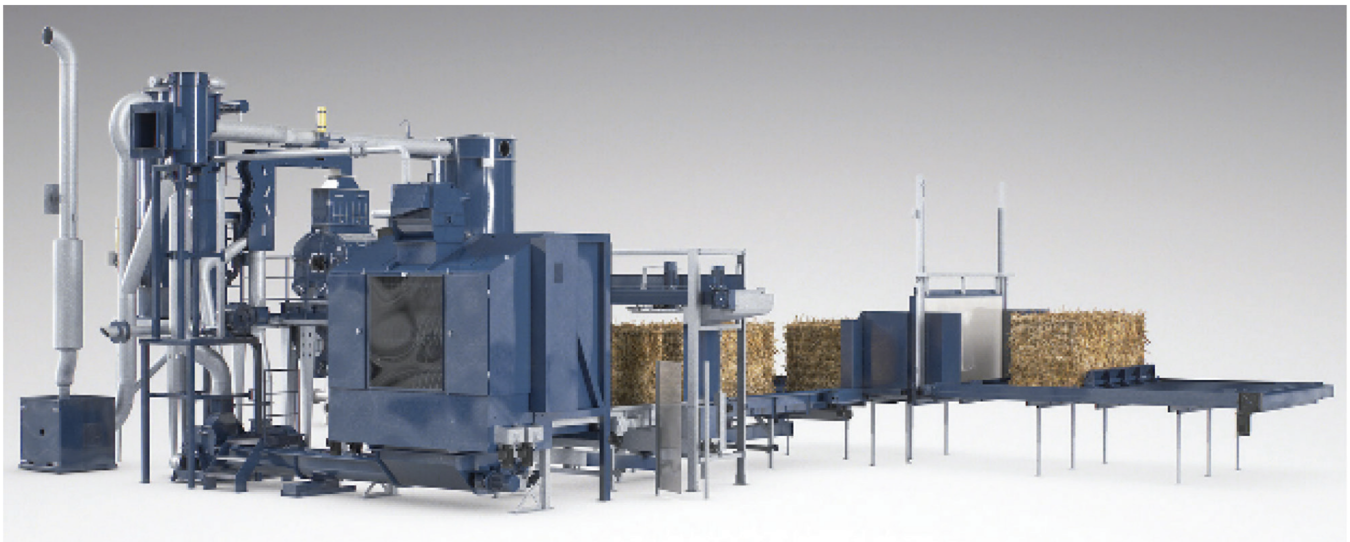


Fig 5.7 – LinKa and Euromilling mini-complex for specialized straw milling

Fig. 5.8 – Cattle manure before and after processing in a bioextruder

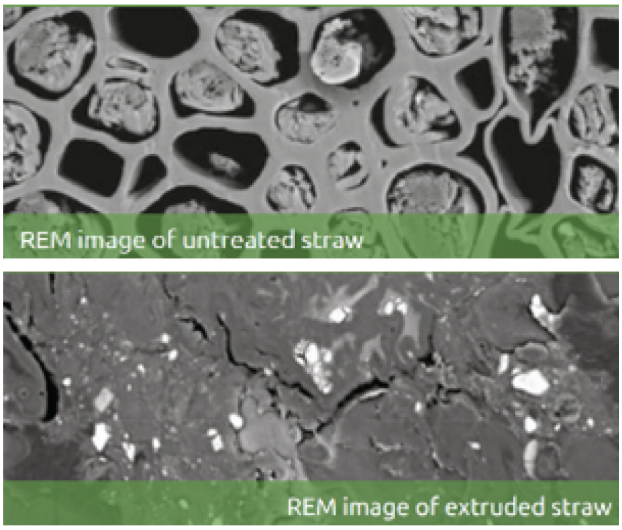


Fig. 5.8 – Structure of raw straw and straw treated in a bioextruder

pressure and tension release cycles as well as the increased temperature in the machine. The biogas yield increases due to the multiple increased surface. According to the company, the increase in biogas yield as a result of extrusion ranges from 14 to 70%, in particular, for straw this index was 32-35%. The structure of straw before and after extrusion is shown in **Fig. 5.8.**

A series of extruders with a capacity of 0.3-8.5 t/h is used for different types of raw materials **(Table 5.4).** To process straw in a bioextruder, it will be necessary to add moisture with digestate recycle or liquid substrate or water, so that the content of TS at the inlet is no more than 50-60%. The consumption of electrical energy depends on both the productivity of the model and the type of raw materials being processed and its humidity.

Table 5.4 – Technical characteristics of Lehmann bioextruders

Throughput perfomance (average values)	Maize and grass silage	Greenwaste, solid manure	Wilted grass sillage	Straw	Mixture (incl. straw)
% DM	30	30	25	50 - 60	30 - 35
MSZ B 44e	1.5 - 3.2 t/h	1.4 - 3.2 t/h	1.8 - 3.2 t/h	0.5 - 0.8 t/h	2.2 - 3.4 t/h
MSZ B 60e	2.0 - 3.5 t/h	1.8 - 4.0 t/h	2.5 - 3.5 t/h	0.6 - 1.0 t/h	2.5 - 3.5 t/h
MSZ B 74e	4.5 - 7.0 t/h	3.5 - 6.5 t/h	3.5 - 6.0 t/h	1.2 - 3.0 t/h	3.0 - 6.5 t/h
MSZ B 90e	4.9 - 7.8 t/h	4.0 - 7.5 t/h	4.0 - 7.3 t/h	2.0 - 3.4 t/h	4.0 - 6.0 t/h
MSZ B 110e	5.2 - 8.5 t/h	4.5 - 8.0 t/h	4.5 - 8.0 t/h	1.6 - 4.0 t/h	4.5 - 8.0 t/h
Energy consumption, kWh/t	6.0 - 14.0	2.5 - 12.5	5.0 - 12.5	30 - 45	8.0 - 18.0

The design of the extruder allows it to be placed outdoors, however, for quick installation and construction, the company has developed a ready-made solution for placing the extruder in a marine container **(Fig. 5.9).**

MethaPlanet has developed a technological solution **Maxximizer** for the specialized production of energy pellets from agrobiomass, in particular straw and litter manure **(Fig. 5.10).**

With the help of a dedicated extrusion technology for pretreatment of straw-containing raw materials before pelletizing, it is possible to achieve a significant increase in the methane yield from energy pellets, even in comparison with pellets produced using traditional equipment. The company claims that the laboratory-confirmed methane yield from such energy pellets is 312 Nm^3CH_4 per ton (fresh weight), and the yield obtained under real conditions is 361 Nm^3CH_4/t, which in terms of organic matter is 357 Nm^3CH_4/tVS and 413 Nm^3CH_4/tVS, respectively. Compared to the methane yield from typical wheat straw pellets, this is 19% and 38% more, respectively. **Fig. 5.11** shows how the use of energy pellets allowed for a higher methane yield in a short period of up to 45 days, compared to untreated cattle manure.

Fig. 5.9 – Bioextruder layout

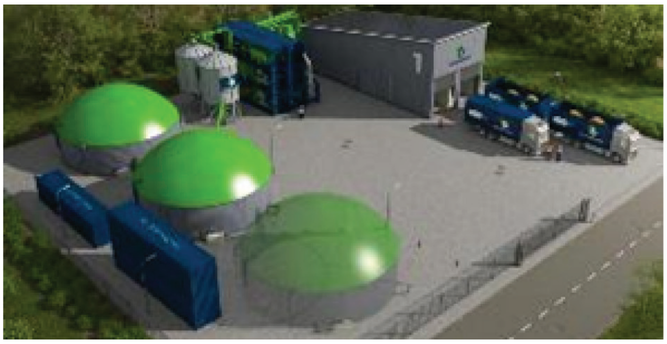


Fig. 5.10 – Layout of Maxximizer equipment with biogas plant

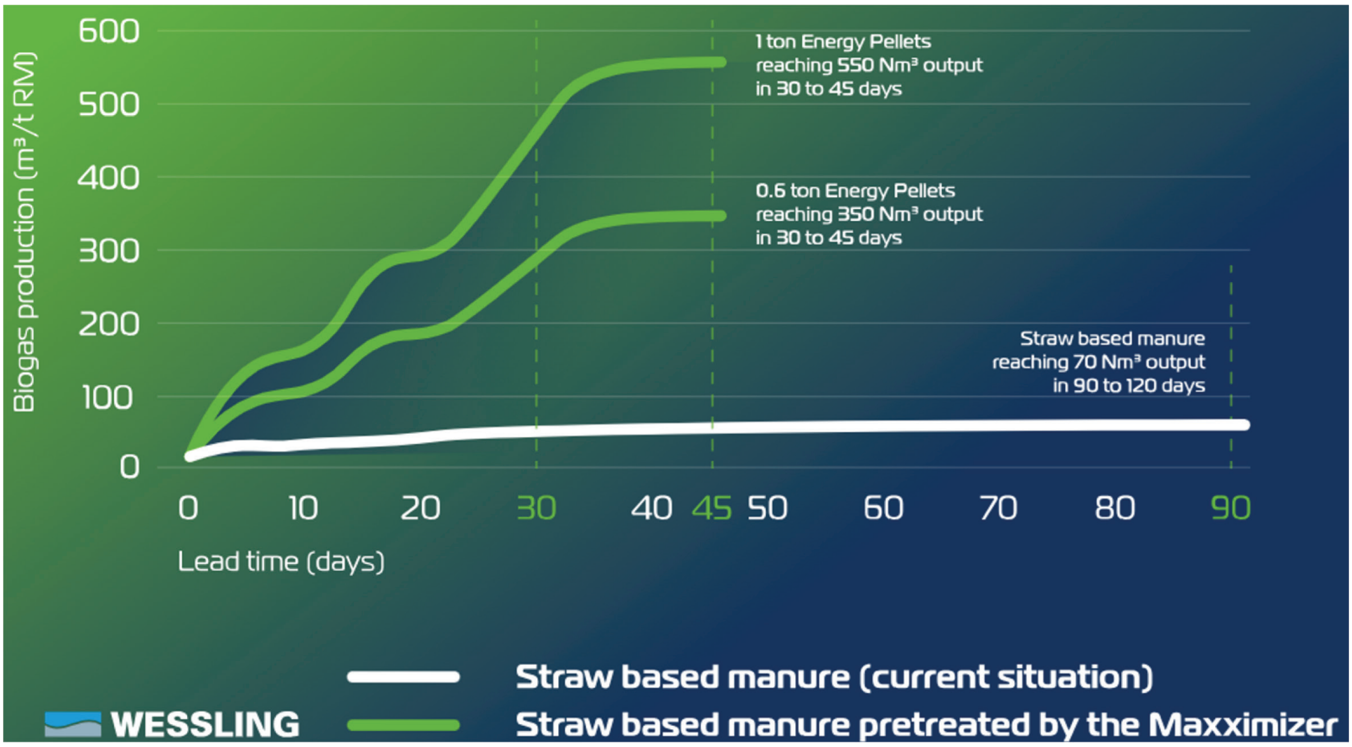


Fig. 5.11 – Comparison of CH_4 yield from energy pellets produced using Maxximizer technology and untreated cattle manure

Technological solutions for anaerobic digestion of crop residues

SECTION 6

Lignocellulosic biomass, such as straw or corn stover, can be processed in most of known types of anaerobic bioreactors and technological schemes based on them. At the same time, such raw materials must be prepared in an appropriate way, by one of the methods discussed in **Section 5** or by any other innovative method that is cost-effective.

The process of anaerobic digestion occurs in 4 main stages: 1) hydrolysis, 2) acidogenesis, 3) acetogenesis and 4) methanogenesis. The course of each stage is the result of the metabolism of different groups of bacteria, which are characterized by different optimal growth conditions. All 4 stages of the process can occur in the bioreactor simultaneously, or can be separated in space, with the course of individual stages in separate bioreactors.

The main technological modes of anaerobic digestion are shown in **Fig. 6.1.** All these modes are generally applicable to agricultural raw materials and have practical implementation. However, among biogas plants, that operate on agricultural raw materials, the most widespread is (semi-) continuous complete mixing mode of operation in CSTR type reactors.

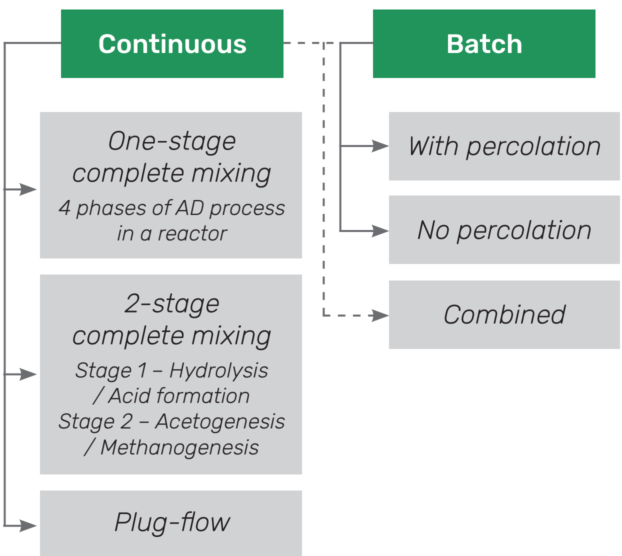


Fig. 6.1 – Main types of technological regimes of anaerobic digestion

In operating biogas plants, the anaerobic digestion process is usually implemented according to 2 main approaches, namely:

> ***a single-stage process**, in which all 4 stages occur simultaneously in one bioreactor;*
>
> ***a two-stage process,** in which the first two stages, hydrolysis and acidogenesis, are implemented in the 1st stage bioreactor, and acetogenesis and methanogenesis in the 2nd stage reactor.*

In both approaches are used post-digesters – air-tight tanks, made similar to main digesters, which function is to stabilize the biological processes and collect residual volumes of biogas.

The single-stage process is most often implemented for the types of raw materials that are easily biodegradable (for example, manure, corn silage, cover crop silage, sugar beet pulp). It can also be implemented to the biogas production process from lignocellulosic biomass, such as straw or corn stalks. However, this approach requires careful pre-treatment of such raw materials to ensure sufficient homogenization, loss of hydrophobic properties and a rate of biological decomposition of straw, comparable to the main types of raw materials.

The second approach is often used for fermentation of more complex types of raw materials, including crop residues, and when technologies with high organic loads are used. This approach requires straw being hydrolysed in a separate reactor, ensuring optimal process conditions by adding the necessary amount of complementary raw materials and/or macro- and microelements. Two-stage fermentation is a more complex technological process, as it requires control of two different sets of parameters in bioreactors, as well as careful coordination of the rate of both processes and the yield of intermediate and target products of the technology. The advantage of this approach may be the acceleration of the overall process of biodegradation of organic matter of straw into biogas, including through the use of specialized high-performance enzymes at the hydrolysis stage.

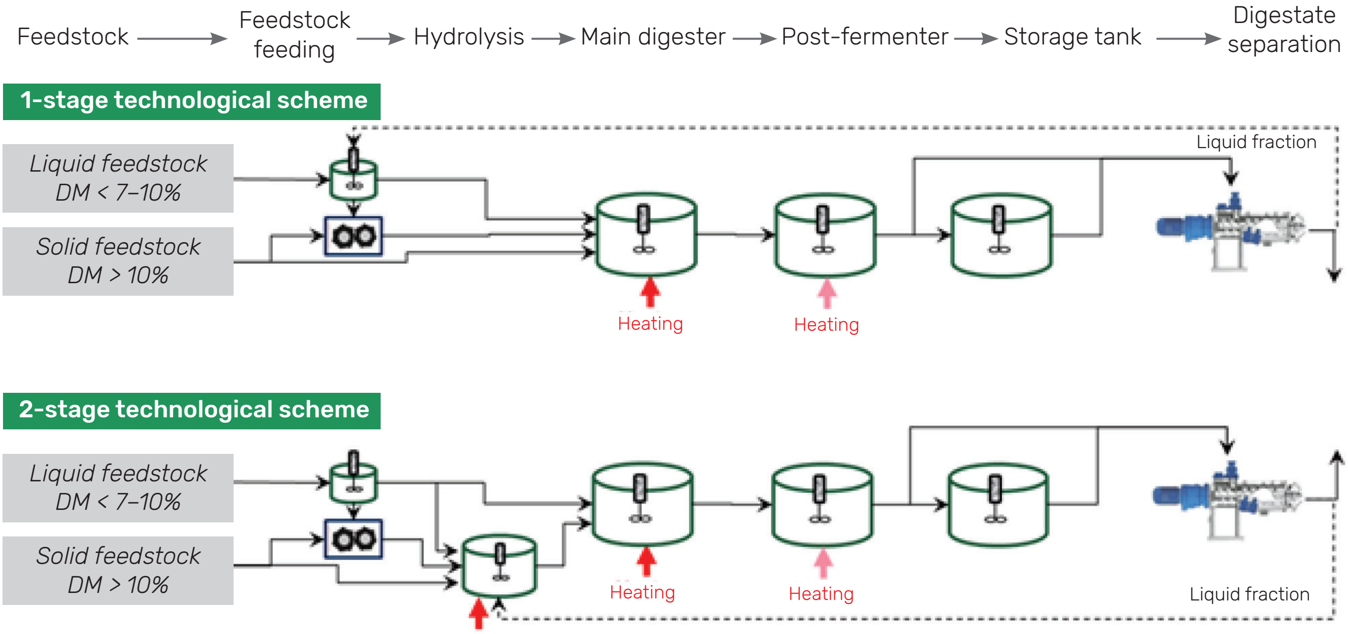


Fig. 6.2 – Examples of technological schemes of biogas plants

Fig. 6.2 shows a typical composition of the ***main parts*** of a biogas plant operating in 1-stage and 2-stage modes. Such schemes are universal and can be used for various mixtures of liquid and solid types of raw materials. 2-stage fermentation schemes are more complex, require the construction of an additional hydrolysis reactor, which accordingly increases their cost. The presence of post-digester in the technological scheme allows for additional collection of up to 10-15% of biogas and to a greater extent stabilize the formed digestate before sending it to the storage tank. At the same time, there are examples of biogas plants, in particular in Ukraine, with the technological process implemented in 1-stage mode without the use of post-digester. Post-digesters heating is not a mandatory option and can be used depending on the efficiency of the process in the main reactors.

The actual composition and size of the main parts of the biogas complex are determined by the types of raw materials used and the required hydraulic retention time to achieve the target efficiency of bioconversion of organic matter into biogas. The degree of bioconversion shows the proportion of the mass of biologically available organic matter that has turned into biogas, and is maintained at 90-95%. Different types of raw materials, depending on the method of their pretreatment, require different retention times in bioreactors. For example, corn silage requires 40-45 days of fermentation, manure – 25-35 days, mechanically crushed straw – 50-60 days. Mixing different types of raw materials, for the same retention time, will lead to a different level of bioconversion for each type of raw material. Increasing the retention time of raw materials will require an increase in the volume of all technological structures, the capacity of technological equipment and, accordingly, the consumption of energy and consumables.

For biogas production from straw or corn stover, batch fermentation technologies **(Fig. 6.3)** or technologies with high-load bioreactors of "dry"

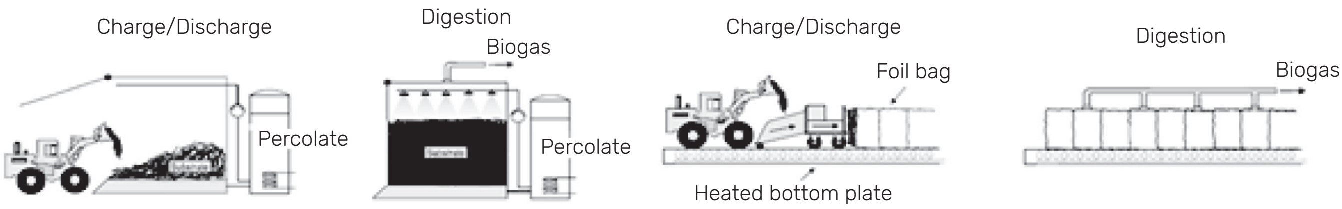
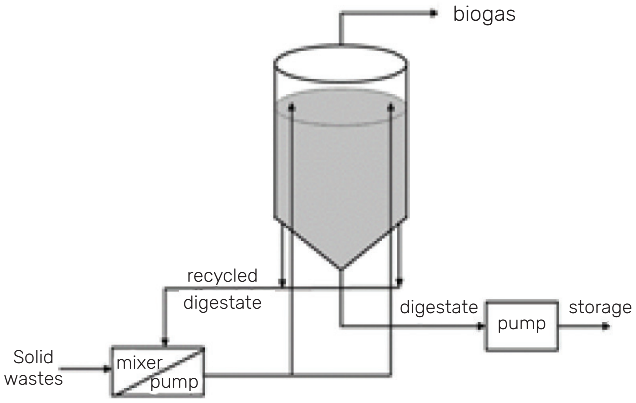


Fig. 6.3 – Examples of batch anaerobic digestion technologies:
a) scheme with percolate reactor; b) scheme with tunnel reactor



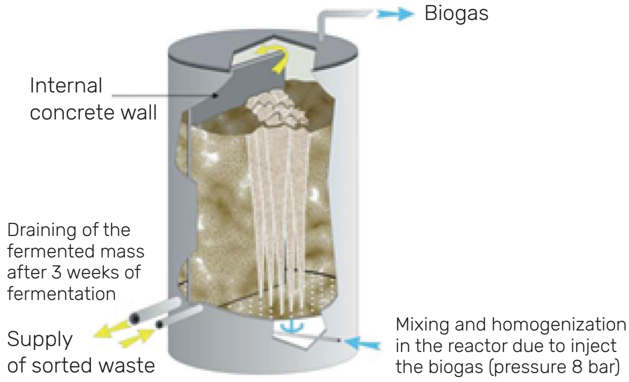


Fig. 6.4 – Examples of technologies with high-load dry-type bioreactors:
a) scheme with DRANCO reactors; b) scheme with VALORGA reactor

type, which are typically used for the fermentation of the organic fraction of MSW **(Fig. 6.4)**, can also potentially be used. However, there are currently no known cases from open sources of the use of such technologies for the fermentation of straw.

The advantages of batch fermentation systems are as follows:

> *suitable for fermentation of stacked solid types of raw materials, for example, straw in rectangular bales, which will not require any pre-treatment or even removal of cords;*
>
> *less sensitive to impurities in the raw materials, which will allow the use of relatively "dirty" technologies for collecting crop residues;*
>
> *less sensitive to environmental parameters, which will reduce or even eliminate the need for complementary types of raw materials;*
>
> *consume less electricity;*
>
> *minimal yield of the liquid fraction of the digestate.*

The main disadvantages of such technologies are increased methane emissions when loading raw materials and unloading the fermented mass, as well as unstable gas composition and volume. To equalize the composition and volume of biogas, it is necessary to build a number of separate reactors, which will accordingly increase the cost of the entire project. In addition, after periodic fermentation of baled straw, it will practically not change structurally and will require further processing before being applied to the fields.

Agronomic, environmental and energy aspects of using crop residues for biomethane production

SECTION 7

Agronomic aspects

Straw as an organic fertilizer is used to form humus in the upper soil layer. Maintaining the proper balance of humus contributes to the biological activation of the soil, as well as its anti-erosion protection. In order for straw to become a truly valuable organic fertilizer, and not a filler that interferes with tillage, it must decompose as quickly as possible. Straw decomposes faster with good air access to the soil (under aerobic conditions). Deep plowing of straw causes an adverse effect, because when it decomposes in the lower layers of the arable horizon, volatile fatty acids are formed, which negatively affect the root system of plants. When applied to the upper third of the arable layer, straw decomposes faster and the accumulation of harmful substances is not observed. Due to the poverty of straw in nitrogen (C:N=60-100), it takes 40-50 kg/ha of soil nitrogen for its own mineralization until the ratio C:N=20 is reached. Therefore, in the first period of their growth and development, plants experience a lack of nitrogen if nitrogen from mineral fertilizers is not added to the soil along with straw[85].

From an agronomic point of view, the use of crop residues for energy needs is considered as a factor in reducing humus reserves and reducing the application of organic fertilizers. At the same time, the production of biomethane from crop residues involves returning them in a transformed form with digestate, which can be considered a sustainable approach, since with digestate almost all macro- and microelements are returned, as well as up to 50% of organic carbon. At the same time, the organic nitrogen contained in native straw is returned in a mineralized ammonium form, easily accessible to plants.

According to this approach, there is no reason to limit the use of crop residues for the production of biogas and biomethane. At the same time, straw is a resource that has significant competitive demand in other areas of application. Therefore, the share of straw that can be taken from the field for biomethane production can be determined for a specific enterprise and region individually. Analysis of possible shares of crop residue removal from fields used by farmers from different countries of the world[86], for energy needs shows that 15-50% of the theoretical potential of crop residue formation can be used.

Environmental aspects

The use of crop residues for biomethane production will have an impact on the balance of greenhouse gas emissions, but whether this balance is positive or negative and what its value will depend, in particular: on the applied fermentation technologies, CO_2 utilization from biogas upgrading, climatic conditions in the region, type and characteristics of soils, applied arable land treatment technologies and digestate application technologies. Further application of digestate from crop residues to fields will also have an impact on the carbon stock in the soil, on the pollution of groundwater and surface water, as well as ammonia emissions into the atmosphere.

In the study[87] the effect of straw return on GHG emissions from cornfields were analyzed. The meta-analysis results indicated a complex interrelationship between straw return and GHG emissions, influenced by region, gas type, nitrogen rate, environmental factors, and soil conditions. Returning straw to the field resulted in a significant increase of 140% in CO_2 emissions, with nitrogen rate being the main factor affecting this increase. Straw return increased CH_4 emissions by 3%, with soil organic carbon content being the most notable factor affecting CH_4 emissions. The amount

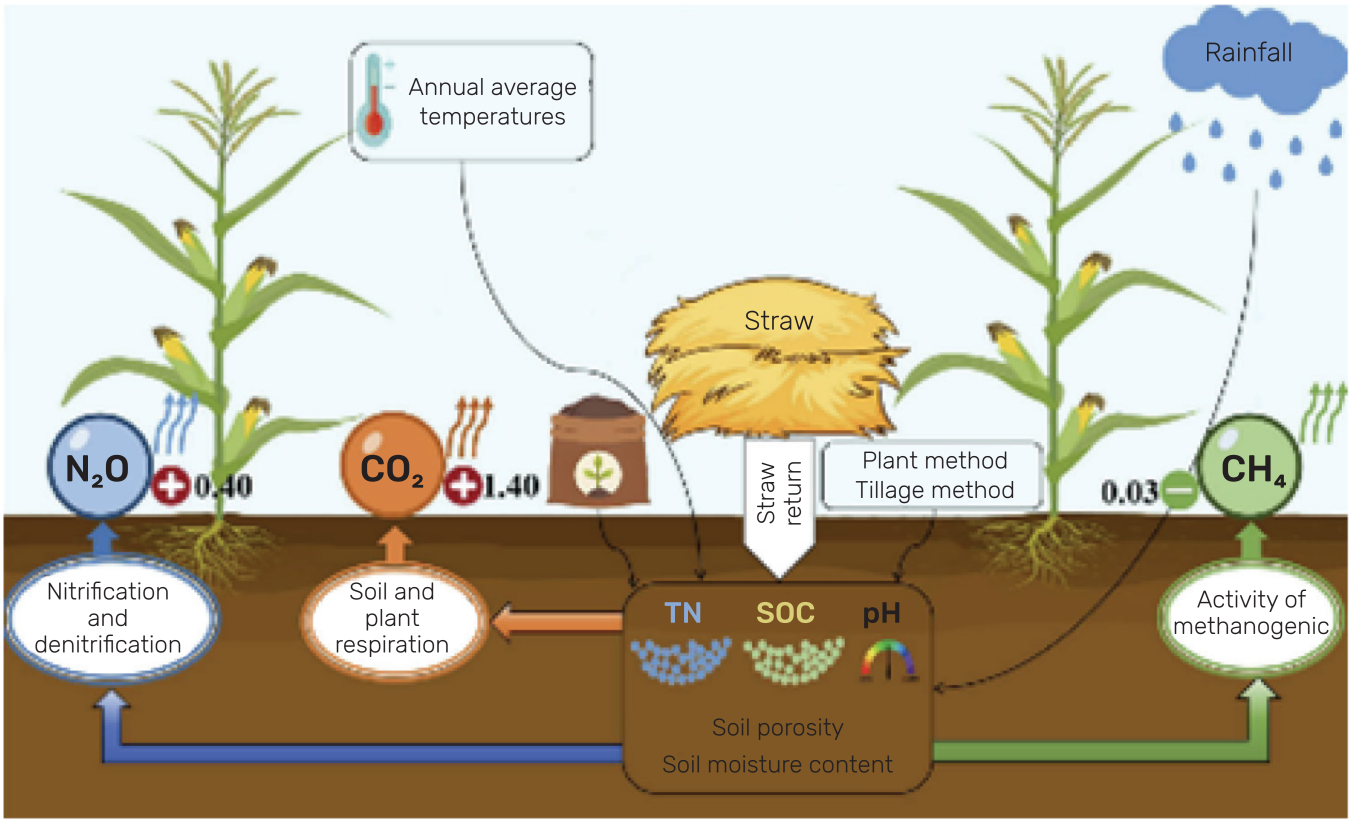


Fig. 7.1 – Conceptual map of the impact of straw returning on greenhouse gas emissions[103]

Notes: The plus sign in red indicates an increase, while the minus sign in green indicates a decrease. The number next to the sign represents the corresponding effect value.

of nitrogen applied was the most important factor affecting N_2O emissions under straw return conditions. Returning straw to fields increased N_2O emissions by 40% compared with not returning it. **Fig. 7.1** provides a theoretical foundation for future justifications for straw returns.

Applying digestate obtained from crop residues to fields will also lead to greenhouse gas emissions. Nitrous oxide N_2O emissions can occur during nitrification-denitrification of ammonium nitrogen[88]. N_2O emission rates can range from 0.5% to 5% of the total nitrogen applied, depending on soil type and pH, moisture and temperature, timing and method of digestate application. Nitrous oxide emissions can increase if digestate has high ammonium content, when application is followed by wet conditions or rainfall, or the field has poor aeration or compaction[89].

Organic nitrogen during anaerobic digestion process is transformed into a mineralized form that is easily available to plants, so choosing the right techniques and periods for applying digestate will contribute to the fastest possible absorption by plants and minimizing emissions into the atmosphere. Part of the unabsorbed nitrogen can further infiltrate into the soil and enter groundwater, causing its pollution. To prevent this, many European countries strictly control the application of nitrogen fertilizers, in particular digestate, which is regulated by the Nitrates Directive. The Nitrates Directive (Council Directive 91/676/EEC) mandates Member States to designate Nitrate Vulnerable Zones (NVZs) to reduce water pollution caused by nitrates from agricultural sources.

The introduction of digestate containing an active mass of anaerobic bacteria will also contribute to the decomposition of organic residues accumulated in the soil, with the release of methane. Additional CO_2 emissions may arise from the oxidation of residual organic carbon in the digestate.

The negative balance of GHG emissions when using crop residues for biomethane production will be formed due to the following factors:

> *reduction of GHG emissions from not ploughing crop residues into the soil;*
>
> *reduction of GHG emissions from replacing fossil fuel energy with biomethane;*
>
> *reduction of GHG emissions from replacing nitrogen fertilizers when applying digestate into the soil;*
>
> *reduction of the mass of carbon returned to the soil;*
>
> *reduction of emissions due to the utilization or storage of CO_2 from biogas upgrading.*

The positive GHG emissions balance will be formed due to the following factors:

> *use of fossil fuels for operations of collection and logistics of crop residues;*
>
> *use of electricity from the grid, if applicable;*
>
> *cultivation, collection and logistics of biomass used for production of electricity and heat for the biomethane complex's own needs, if applicable;*
>
> *CH_4 emissions with biogas due to leaks and release of residual methane from digestate accumulation and storage sites;*
>
> *GHG emissions generated when digestate is applied to soils.*

As will be shown in the example of GHG emissions assessment given in **Section 8,** biomethane produced from wheat and corn straw will have a negative carbon intensity provided that CO_2 from biogas upgrading is utilized. If CO_2 is released into the atmosphere, the carbon intensity will be positive, but will still meet 65% GHG emission reduction level for transport fuels required by the EU REDII Directive.

Energy aspects

From the energy balance point of view, the use of straw and corn stover for biomethane production is justified, as it allows to obtain more energy in biomethane than was spent on its production throughout the entire supply chain.

For example, from 1 ton of wheat straw with a moisture content of 15%, approximately 200-240 Nm^3CH_4 can be obtained, which is equivalent to 7180-8616 MJ of energy. The entire supply chain of such raw materials to the biogas plant will require the consumption of 4.316 L/t of diesel fuel, which is equivalent to 155 MJ/t of energy **(Table 7.1).**

To meet the own needs of the entire biomethane complex through cogeneration on biogas from corn silage, it will be necessary to consume approximately 2.94 L/t of diesel fuel. Thus, the total energy consumption of diesel fuel to ensure the production of biogas from straw will be 261 MJ/t, and from corn silage – 327 MJ/t. This corresponds

Table 7.1 – Estimated values of diesel consumption when harvesting wheat straw, corn stover and corn silage as raw materials for biogas production

Diesel fuel consumption	Value	Wheat straw (bales)	Corn stover (bales)	Corn silage
TOTAL, including:	L/t	4.316	6.146	3.211
	MJ/t	155	221	116
Growing (corn silage) and harvesting	L/t	3.6	5.5	2.155
	MJ/t	130	198	78
Transportation to the warehouse and warehouse operations	L/t	0.46	0.39	0.8
	MJ/t	117	14	29
Operations within the biomethane complex	L/t	0.256	0.256	0.256
	MJ/t	9	9	9

to 3.3% (for straw) and 4.9% (for corn silage) of the energy content of biomethane produced from these types of raw materials.

Provided that electrical energy will be consumed from the network, and own needs in thermal energy will be covered by the consumption of other biomass, the total energy consumption will be 3197 MJ/t of a mixture of straw and corn silage (for the example considered in **Section 8**). Thus, this will be approximately 44% of the energy contained in biomethane produced from a mixture of straw and corn silage.

Thus, the energy balance of using wheat straw and corn stover for biomethane production can be considered positive, even if the biomethane complex supplies electricity for its own needs from the grid.

Feasibility study of biomethane production from crop residues

SECTION 8

To assess the technical and economic parameters of the project on biomethane production from crop residues, a model of raw material supply from an agricultural enterprise with a total of 10 thousand hectares of land in a compact location within one operational district, as well as a pig farm with an average livestock of 18 thousand heads, is considered. At the same time, a scenario is considered in which, for biomethane production, 9,600 t/year of wheat straw (85% DM) is harvested from an area of 2400 hectares and 8550 t/year of corn stalks (75% DM) from an area of 1,900 hectares (*see* **Section 4** *for more details*), and 90 thousand t/year of liquid pig manure (4% DM) is also used.

The use of manure in advanced biomethane production projects allows additional greenhouse gas emissions reduction, and, therefore, lowers biomethane`s carbon intensity. This, accordingly, can increase the demand for such biomethane and possibly the price of its sale when exported to the European market of renewable biofuels. Besides, the use of liquid pig manure is justified from the technological point of view, allowing to compensate for the need of additional hydration during digestion of dry crop residues in wet-type bioreactors, as well as to balance the carbon to nitrogen ratio in the mixture to the optimal level.

It is assumed that the collected mass of wheat straw and corn stover in bales will be delivered to the main warehouse in the close proximity to the biomethane production complex, where it will be stored and supplied for biogas production throughout the year from. The approximate area of the main warehouse is 6 hectares. The mass loss of the straw dry matter during the storage period is taken at the level of 3%, corn stover – 5%.

Three main project concepts were considered and analyzed. The two main concepts differ by the method and equipment for straw and corn stover pre-treatment. **Concept 1** involves pre-treatment using MSZ-B 110e bioextruders manufactured by Lehmann-UMT GmbH, discussed in **Section 5**. Before feeding into the receiving hopper of the bioextruder line, the bales are pre-broken and the straw and corn are crushed. **Concept 2** involves the production of pellets, both from straw and corn stover. A separate drying complex is used to dry the corn stover to an acceptable moisture content for the granulator. The total capacity of the granulation line manufactured by Radviliskis Machine Factory is 2 t/h. Concept 1 and Concept 2 assumes that the produced biomethane will be supplied to GTS of Ukraine with the selling of guarantees of origin (GoO) on the European market of renewable biofuels, and food-grade carbon dioxide will be sold on the domestic market. To assess the impact of the production and sale of liquefied CO_2 on the profitability of the project, an additional option based on Concept 1 was considered, where CO_2 will simply be released into the atmosphere (hereinafter referred to as **Concept 3**).

To meet the own needs of the entire biomethane complex in electricity and heat, including the pre-treatment lines for crop residues, it is planned to produce part of the biogas from corn silage with its subsequent combustion in a cogeneration plant. For the ***concept 1*** of the project, it will be necessary to supply 16,994 t/year of silage with a 35% DM content, for the ***concept 2*** – 22,738 t/year. With a fresh mass yield of corn silage of 50 t/ha, it will be necessary to allocate about 340 ha and 455 ha of land for each concept, accordingly. Using part of produced biogas to meet the complex's own energy needs is considered as a way to reduce the carbon footprint of the produced biomethane, and therefore increase the possible price of guarantees of origin for it.

All the project concepts of the biomethane production provides that straw, corn stover and corn silage will be supplied by a separate division of the agricultural company at a price that takes into account profitability at the level of 25%. At the same time, the costs of crop residues storing and ensiling of corn silage, as well as the costs of supplying all types of raw materials from storages to the biogas plant, will be included in the costs of the biomethane project. The resulting digestate is expected to be applied to the company's fields for the main crops. It is assumed that the liquid fraction of the digestate will be accumulated in the lagoon for six months and then applied to the fields twice a year. The costs of transporting and applying of the digestate onto the fields are not included in the biomethane project costs.

All the project concepts involve the production of biogas in an agricultural-type biogas plant with horizontal cylindrical reactors, which will include the main digesters and a post-digester. A part of the produced biogas, after preliminary drying and removal of hydrogen sulfide, will be fed to a CHP unit for the production of electricity and heat. The rest, the main part of the biogas, will be fed for biogas upgrading to biomethane. The project considers the option for carbon dioxide upgrading to the food-grade quality and liquefaction of CO_2 released during the biogas upgrading process. A boiler plant on agropellets is also envisaged, which will provide heating of the bioreactors during biological start-up, as well as backup in case of downtime of the biogas CHP. The estimated equivalent cost of digestate can be 2.42 euros/t. The financial model takes into account the price of digestate for the agricultural company at the level of 1.5 euros/t, excluding VAT.

The estimated biogas yield for ***concept 1*** is 10.84 million Nm³/year **(Table 8.1)**, for ***concept 2*** – 12.44 million Nm³/year **(Table 8.2)**.

Table 8.1 – Estimated biogas yield and raw material composition (concept 1)

Index	Unit	Mixture, total	Feedstock:			
			Wheat Straw	Pig Manure	Corn Stover	Maize Silage
Feedstock supply	t/year	**123 409**	9 312	90 000	8 123	15 974
Assumed biochemical methane potential yield (BMP)	$Nm^3CH_4/t\ VS$	**287.3**	270	360	270	350
	Nm^3CH_4/t	**183.2**	215.7	12.2	186.3	113.9
Biogas	Nm³/t VS	**508.7**	490.9	553.8	490.9	636.4
Efficiency	%	**95**	95	95	95	95
Production of CH_4	Nm^3CH_4/day	**16 771**	5 229	2 867	3 939	4 737
	$Nm^3CH_4/year$	**6 121 361**	1 908 434	1 046 520	1 437 561	1 728 846
Production of biogas	Nm³/day	**29 690**	9 507	4 411	7 161	8 612
	Nm³/year	**10 837 014**	3 469 880	1 610 031	2 613 747	3 143 356
Production of CO_2	Nm^3CO_2/day	**12 623**	4 183	1 500	3 151	3 789
% CH_4	%	**56.5**	55	65	55	55
% CO_2	%	**42.5**	44	34	44	44
Total nitrogen content	kg N/t	**3.3**	4.3	2.8	5.6	4.5
C:N ratio	-	**23.9**	84.6	5.7	55.2	34.4

Table 8.2 – Estimated biogas yield and raw material composition (concept 2)

Index	Unit	Mixture, total	Feedstock:			
			Wheat Straw	Pig Manure	Corn stover (pellets)	Maize Silage
Feedstock supply	t/year	**126 626**	8 619	90 000	6 633	21 374
Assumed biochemical potential of methane yield (BMP)	Nm^3CH_4/t VS	**307.1**	300.0	360.0	300.0	350.0
	Nm^3CH_4/t	**191.2**	253.8	12.2	248.4	113.9
Biogas	Nm^3/t VS	**545.6**	545.5	553.8	545.5	636.4
Efficiency	%	**95**	95	95	95	95
Production of CH_4	Nm^3CH_4/day	**19 187**	5 693	2 867	4 289	6 338
	Nm^3CH_4/year	**7 003 218**	2 078 072	1 046 520	1 565 344	2 313 281
Production of biogas	Nm^3/day	**34 083**	10 352	4 411	7 797	11 523
	Nm^3/year	**12 440 390**	3 778 314	1 610 031	2 846 080	4 205 966
Production of CO_2	Nm^3CO_2/day	**14 556**	4 555	1 500	3 431	5 070
% CH_4	%	**56.3**	55	65	55	55
% CO_2	%	**42.7**	44	34	44	44
Total nitrogen content	kg N/t	**3.4**	4.5	2.8	6.8	4.5
C:N ratio	–	**24.3**	84.6	5.7	55.2	34.4

As can be seen from the above indicators, mixing crop residues (14.1% by fresh weight and 60.4% by DM) with pig manure and corn silage allows achieving an acceptable C:N ratio in the mixture at the level of 24, and at the same time ensuring an acceptable DM content in the fermented mixture in bioreactors – at the level of 8.3% for ***concept 1*** and 7.8% – for ***concept 2***. It is expected that the estimated biogas yield from the mixture will be achieved for a total fermentation time of 57 days (***concept 1***) and 45 days (***concept 2***). The reduction in hydraulic retention period in ***concept 2***, compared to ***concept 1***, is justified by the improvement of the kinetics of decomposition of organic matter of crop residues in granular form. This, accordingly, allows reducing the required working volume of bioreactors by up to 20%.

The estimated outputs of the target products in the considered project concepts are given in the **Table 8.3.**

The project concepts take into account the connection to the electricity grid in order to guarantee the uninterrupted operation of all equipment of the biomethane complex, however, it is assumed that all the complex's electrical energy needs will be covered by the operation of the biogas CHP. The total connected electrical load for ***concept 1*** is 1,090 kW_e, ***concept*** 2 – 1,660 kW_e, ***concept 3*** – 880 kW_e.

To maintain the required temperature in the bioreactors, it will be necessary to supply 7.7-8.1 GWh/year of thermal energy. These needs will be fully covered by waste heat from the biogas CHP and waste heat from the biogas upgrading process.

The estimated investment in the project (CAPEX), including VAT and customs duties, amounted to 13.93 million euros for ***concept 1***, 13.91 million euros for ***concept 2***, and 11.95 million euros for ***concept 3*** **(Table 8.4).** The specific investment in the biogas production complex is 2071 euros/kW of equivalent electrical capacity of the biogas CHP for ***concept 1***, and 1705 euros/kW for ***concept 2***, which corresponds to the average and below-average market prices for biogas plants of a similar capacity, respectively. A decrease in specific investment for ***concept 2*** is possible due to a decrease in the hydraulic retention period and an increase in the intensity of biogas output.

Table 8.3 – Output of target products in the considered project concepts

Product	Unit	Value per concept:		
		Concept 1 – Biomethane from straw (bioextruded) + liquefied CO_2	Concept 2 – Biomethane from pellets + liquefied CO_2	Concept 3 – Biomethane from straw (bioextruded) only
Biomethane (98% CH_4)	thousand Nm³/year	4 455.3	4 756.9	4 455.3
	MWh/year	43 540	46 488	43 540
Liquefied CO_2 (99.99%)	%	5 561	6 001	0
Digestate, incl.:	t/year	109 760	110 928	107 344
liquid fraction	t/year	21 952	22 186	21 469
solid fraction	t/year	87 808	88 742	85 875

Table 8.4 – CAPEX of considered project concepts

CAPEX item	Cost, thousand euros, including VAT and customs duties		
	Concept 1 – Biomethane from straw (bioextruded) + liquefied CO_2	Concept 2 – Biomethane from pellets + liquefied CO_2	Concept 3 – Biomethane from straw (bioextruded) only
TOTAL	**13 928.2**	**13 908.5**	**11 950.0**
Technology and equipment	**8 964.1**	**8 780.3**	**7 234.6**
Construction and installation	**4 135.8**	**4 288.9**	**3 941.6**
Other	**828.3**	**839.3**	**773.9**
Biogas production complex	6 060.0	5 710.5	5 981.1
Equipment and technology for pre-treatment of straw and corn stover	736.2	800.5	736.2
Machinery and technology for ensiling and transporting silage to the biogas plant	175.5	175.5	175.5
Silo storage	383.4	513.0	305.9
Biogas CHP	956.6	1 114.4	859.0
Backup boiler room	248.4	268.9	215.3
Biogas upgrading complex	2 310.0	2 173.0	2 310.0
CO_2 liquefaction complex	1 485.5	1 485.5	-
Biomethane transfer unit to the gas transmission system (main + backup compressors, 5 km gas pipeline, gas accounting unit, chromatograph)	1 137.4	1 169.5	1 137.4
Machinery and technology for CO_2 logistics	195.1	195.1	-
Connection to the power grid	58.4	120.9	47.8
Machinery and technology for digestate operations	61.7	61.7	61.7
Project design	120.0	120.0	120.0

The lion's share of investment for all considered project concepts falls on the biogas production complex (> 40%). Significant components of the investment are also biogas upgrading complex, CO_2 liquefaction complex, and crop residue pre-treatment equipment. The costs of pre-treatment equipment amounted to 5.3% for *concept 1* and 5.8% for *concept 2.*

The total annual operating expenses (OPEX), excluding VAT, are estimated at 2.08 million euros for *concept 1*, 2.39 million euros for *concept 2*, and 1.89 million euros for *concept 3* **(Table 8.5).** The main project costs are related to the purchase of raw materials and operations for their procurement, transportation and pretreatment – a total of 51-52%. A significant share of the project costs is also made up of labor costs – from 17.4% to 20.0%. The total staff for servicing the entire biomethane complex, including logistics of raw materials and pre-treatment of straw and corn stover, is estimated at 19-20 persons.

The basic values of tariffs and prices adopted in the financial model are given in **Table 8.6.** The basic exchange rate put at 47.07 UAH/euro.

The assessment of the expected price for biomethane was made on the basis of data from biomethane traders, taking into account the estimated carbon footprint of such biomethane.

The calculation of greenhouse gas (GHG) emission reductions was carried out in accordance with the provisions of the RED II Directive, in particular the methodology for calculating emission reductions set out in Annex VI B (biomass fuels). When calculating GHG emission reductions, one of the permitted approaches was applied, namely a combination of calculated values and distributed default values. Distributed default values were used partially for manure and corn silage. The estimated GHG emission reductions for each type of raw material for all considered concepts are given in **Table 8.7.**

Table 8.5 – OPEX of the considered project concepts

OPEX item	Cost, thousand euros, excluding VAT		
	Concept 1 – Biomethane from straw (bioextruded) + liquefied CO_2	Concept 2 – Biomethane from pellets + liquefied CO_2	Concept 3 – Biomethane from straw (bioextruded) only
TOTAL	**2 082.2**	**2 388.3**	**1 886.0**
Raw materials	873.9	873.9	806.3
Raw materials logistics	99.2	72.4	89.0
Biogas production	70.6	67.0	70.6
Pre-treatment of straw and corn stover	85.0	270.2	85.0
Combined production of electricity and heat in biogas CHP	47.8	46.4	47.8
Maintenance of a backup boiler room	9.3	10.0	13.2
Biogas upgrading	109.9	103.4	109.9
Liquefaction of CO_2	30.9	30.9	-
Logistics of liquified CO_2	89.0	96.0	-
Biomethane logistics	242.6	277.8	242.6
Digestate operations	61.7	62.0	59.2
Wage fund	362.4	478.2	362.4

Table 8.6 – Base tariffs and prices adopted in the financial model (excluding VAT)

Index	Unit	Value
Target products		
Biomethane price (concept 1)	euro/MWh	91
Biomethane price (concept 2)	euro/MWh	90
Biomethane price (concept 3)	euro/MWh	82
Liquid CO_2 price	euro/t	133
Digestate price	euro/t	1.5
Raw material		
Wheat straw	euro/t	25.77
Pig manure	euro/t	0
Corn	euro/t	36.84
Corn silage	euro/t	20.95
Storage and logistics of raw materials within the complex		
Wheat straw	euro/t	2.93
Pig manure	euro/t	0
Corn	euro/t	2.67
Corn Silage	euro/t	3.14
Target products logistics		
Liquefied CO_2	euro/(t km)	0.05
Biomethane: tariff at the entry point to GTSU	UAH/(1000 m^3/day)	464.37
Biomethane: tariff at the entry and exit points at interstate connections	euro/(1000 m^3/day)	25.66

As can be seen from the calculation results, all types of raw materials provide the required level of GHG emission reduction of 65% for transport fuels, except for corn silage in project concept 3 without CO_2 utilization from biogas upgrading. The averaged total emissions (E) for the entire final product (BIOMETHANE) were: for ***concept 1*** (-17.33) gCO_{2-eq}/MJ, for ***concept 2*** (-14.05) gCO_{2-eq}/MJ, for ***concept 3*** (+14.94) gCO_{2-eq}/MJ.

Table 8.8 shows the key performance indicators of the project concepts. It can be seen that the production of straw pellets, compared to its pre-treatment in bioextruders, significantly (by 25%) increases the specific electricity consumption per 1 MWh of produced biomethane. The levelized cost of biomethane produced (LCOE) was 53.8 EUR/MWh for ***concept 1***, 55.8 EUR/MWh for ***concept 2***, and 50.4 EUR/MWh for ***concept 3***.

Table 8.9 presents the adopted terms of financing the project. The share of borrowed funds was assumed to be 60% at 8.0% per annum. Equipment depreciation was assumed to be for a period of 15 years, and buildings – for 50 years. The inflation factor was not taken into account in the financial model. The results of the assessment of the main financial indicators are presented in **Table 8.10.**

Table 8.7 – Total emissions for the final product by type of raw material, gCO_{2-eq}/MJ of final product (biomethane)

Emissions assessment component	Wheat straw			Corn			Pig manure			Corn silage		
	K-1	K-2	K-3	K-1	K-2	K-3	K-1	K-2	K-3	K-1	K-2	K-3
Emissions from extraction and cultivation $[e_{ec,n}+e_{td,n}+e_{l,n}-e_{sca,n}]$	2.3	3.6	2.3	3.6	5.2	3.5	0.0	0.0	0.0	18.1	18.1	18.1
Manure credits	0.0	0.0	0.0	0.0	0.0	0.0	-107.9			0.0	0.0	0.0
Application of the e_B bonus (restoration of degraded lands), g CO_{2-eq}/MJ	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Emissions from production (e_r)	13.2	13.9	12.3	13.2	13.9	12.3	13.2	13.9	12.3	13.2	13.9	12.3
Emissions from transportation and distribution of the finished product (e_{td}, product)	4.5	4.6	4.4	4.5	4.6	4.4	4.5	4.6	4.4	4.5	4.6	4.4
Emissions from end use (e_u)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Emission reduction from CO_2 capture and replacement (e_{ccr})	-34.6	-34.8	0.0	-34.6	-34.8	0.0	-34.6	-34.8	0.0	-34.6	-34.8	0.0
Total emissions (E) for the entire final product (BIOMETHANE)	-14.2	-12.4	19.3	-13.0	-10.8	20.6	-124.4	-123.9	-90.9	1.6	2.2	35.1
GHG emission reduction potential for the final product, %	115	113	79	114	111	78	232	232	197	98	98	63

Notes: K-1 – for project concept 1; K-2 – for project concept 2; K-3 – for project concept 3

Table 8.8 – Key Project Performance Indicators (KPIs)

Index	Unit	Value		
		Concept 1 – Biomethane from straw (bioextruded) + liquefied CO_2	Concept 2 – Biomethane from pellets + liquefied CO_2	Concept 3 – Biomethane from straw (bioextruded) only
Project capacity	$MW_{biomethane}$	4.97	5.31	4.97
Specific CAPEX	ths. $EUR/MW_{biomethane}$	2 802	2 614	2 404
Specific OPEX	$EUR/MWh_{biomethane}$	45.5	48.1	43.3
LCOE* for 15 years	$EUR/MWh_{biomethane}$	53.8	55.8	50.4
Total electricity consumption	MWh/year	7 482	9 973	5 981
Specific electricity consumption	$kWh/MWh_{biomethane}$	171.8	214.5	137.4
Carbon intensity of biomethane	$gCO_{2-eq}/MJ_{biomethane}$	-17.33	-14.05	14.94

**LCOE – levelized cost of energy*

Table 8.9 – Terms of financing the project

Index	Unit	Value
Lending rate	%	8.0%
Delayed loan payment	years	1
Lending term	years	7
Corporate tax rate	%	18%
Discount rate	%	10%
Equity	%	40%

Table 8.10 – Economic efficiency indicators of the considered project concepts

Index	Unit	Value		
		Concept 1 – Biomethane from straw (bioextruded) + liquefied CO_2	Concept 2 – Biomethane from pellets + liquefied CO_2	Concept 3 – Biomethane from straw (bioextruded) only
Investments (CAPEX), including:	million euros	**13.93**	**13.87**	**11.95**
Borrowed funds		8.36	8.32	7.17
Own funds		5.57	5.55	4.78
Operating expenses (OPEX), including:	million euros/ year (excl. VAT)	**1.98**	**2.24**	**1.89**
Raw materials		0.97	0.95	0.90
Operating expenses		0.35	0.53	0.33
Logistics of target products		0.39	0.42	0.30
Revenue	million euros/ year (excl. VAT)	**4.87**	**5.15**	**3.73**
Biomethane		3.96	4.18	3.57
Liquefied CO_2		0.74	0.80	-
Digestate		0.16	0.17	0.16
NPV	million euros	**6.07**	**6.25**	**1.23**
IRR	%	**20.6%**	**20.9%**	**12.5%**
PI	-	**0.44**	**0.45**	**0.10**
Simple payback period	years	**5.8**	**5.7**	**7.8**
Discounted payback period	years	**7.6**	**7.5**	**12.1**

Project *concepts 1* and *2*, which involve the liquefaction and sale of CO_2 from biogas upgrading at a price of 133 EUR/t, excluding VAT, showed an acceptable level of profitability with IRR of 20.6% and 20.9% and discounted payback period of 7.6 years and 7.5 years, respectively. Thus, both of the considered technological solutions for the pre-treatment of straw and corn stover are comparable from an economic point of view. The possibility of operating the pelletizing line as a separate production unit, with the supply of pellets to the market, even if circumstances arise for interruptions in the operation of the biomethane complex is an obvious advantage of the *concept 2*. At the same time, in our opinion, biogas production from granulated crop residues have fewer technological risks, compared to any other method of preliminary mechanical pretreatment, due to the fast wetting and loss in floating features in technological tanks.

The considered project *concept 3*, in which CO_2 after biogas upgrading is simply discharged into the atmosphere, significantly loses to the two basic concepts in terms of profitability. The IRR of the project estimated at 12.5% with discounted payback period of 12.1 years, which are not investment-attractive indicators in Ukrainian market conditions. To achieve the same level of profitability as in project *concept 1*, the price level for the produced biomethane should be 97 EUR/MWh, which is unlikely, given the carbon intensity of such biomethane being of 14.94 g $CO_{2\text{-eq}}$/MJ and the current conditions on the market for renewable biofuels in European countries.

Sensitivity analysis of the IRR indicator by the sales price of the main target products shows that the project profitability is significantly affected by the sales price of biomethane **(Fig. 8.1)**, and to a lesser extent by the sales price of liquefied CO_2 **(Fig. 8.2)**. The cost of raw materials also significantly affects the project profitability **(Fig. 8.3)**.

A decrease in the price of biomethane to 80 euros/MWh or an increase in the cost of the project by 20% reduces the level of profitability of the project at IRR 15%. The same degree of decrease in profitability can be observed with the price of purchased raw materials increased by 24-27%, from 31.4 to 39-40 euros/t, including VAT.

The project of biomethane production from crop residues, under the explored conditions and assumptions, can be considered attractive for investment. At the same time, it is quite sensitive to changes in the price of biomethane, liquefied CO_2 and the cost of raw materials. Guaranteed satisfying selling price of biomethane for the long term and finding sales markets for liquefied carbon dioxide with higher profitability can be key of success for such projects. At the same time, the useful utilization of CO_2 at an acceptable price is a necessary prerequisite for obtaining a sufficient price for the produced biomethane and ensuring acceptable economic indicators of the project. Reducing investments in the project will also make it more economically sustainable, however, the probability of a significant (by 15-20%) reduction in investments is rather low.

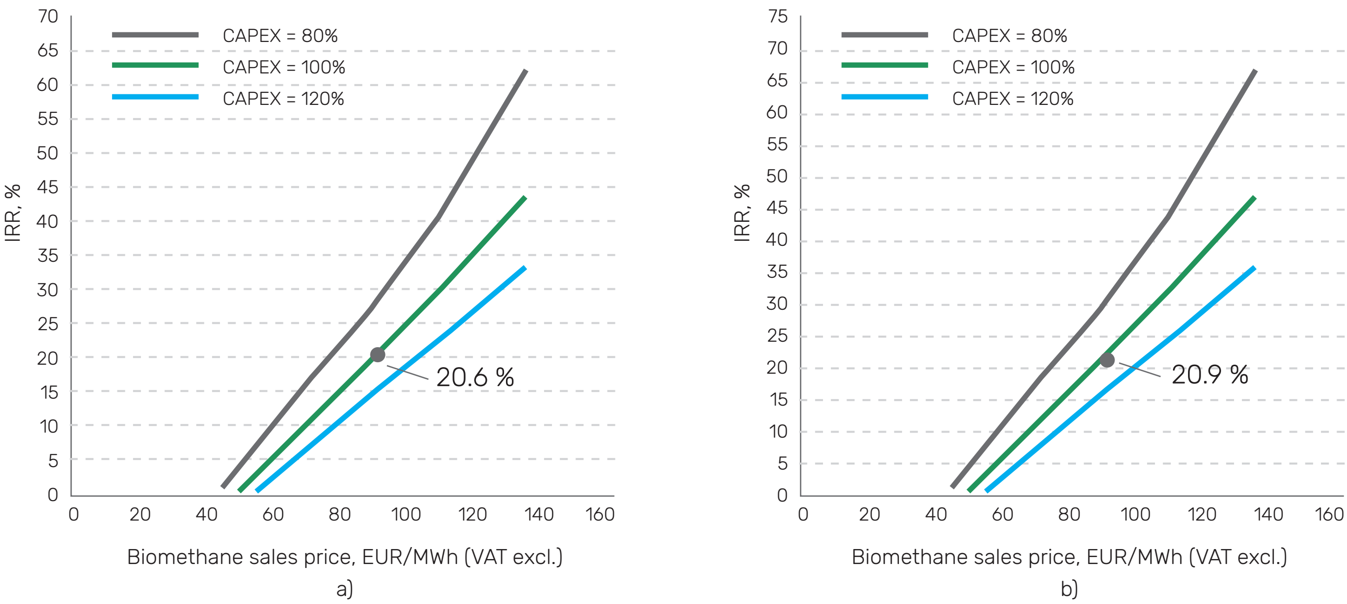


Fig. 8.1 – Dependence of IRR value on biomethane price: a) for the project concept 1; b) for the project concept 2

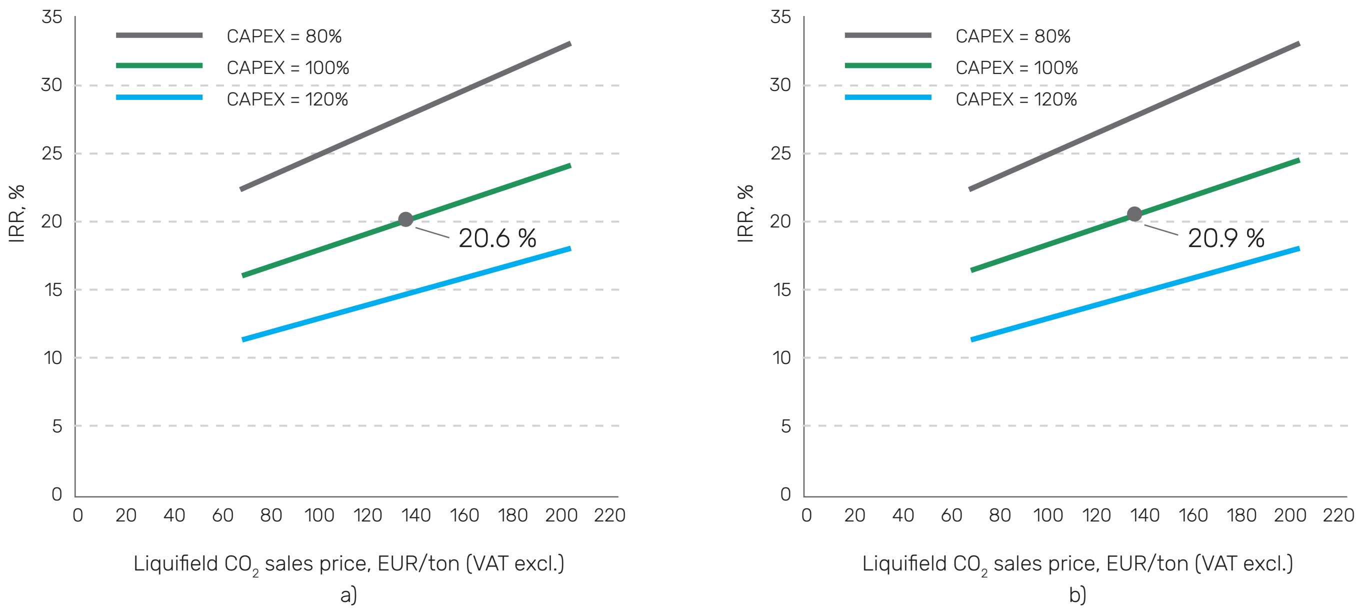


Fig. 8.2 – Dependence of IRR on the price of liquefied CO_2: a) for the project concept 1; b) for the project concept 2

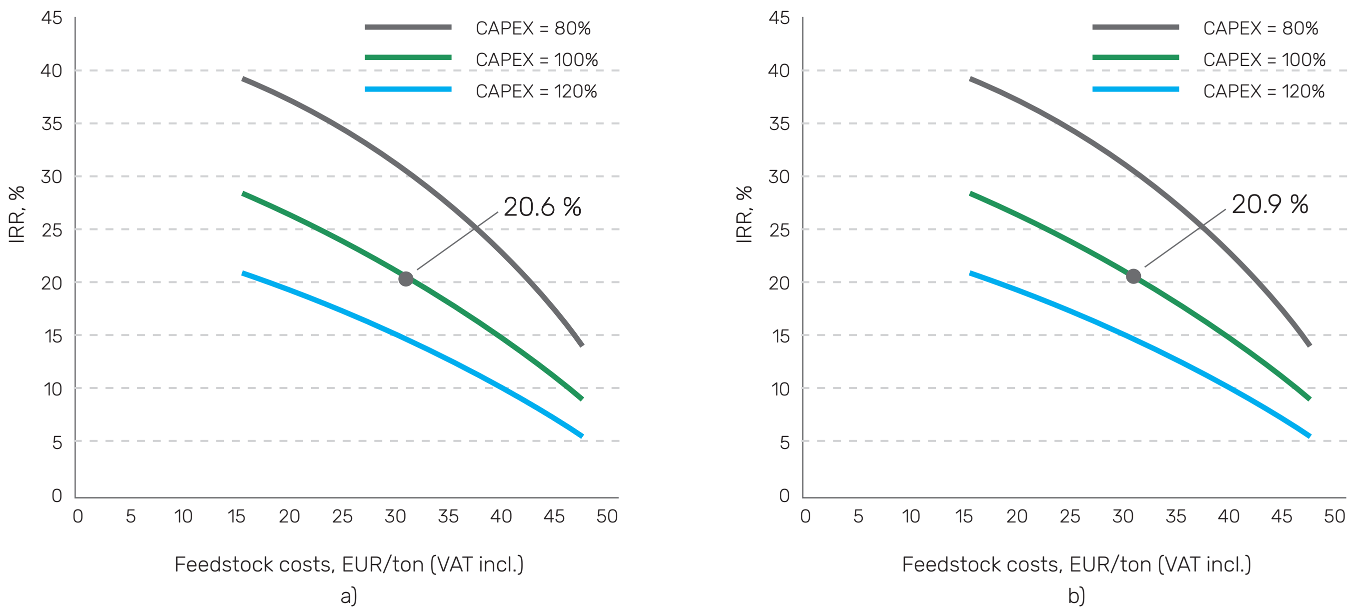


Fig. 8.3 – Dependence of IRR on feedstock (mixture of straw and corn stover) costs:
a) for the project concept 1; b) for the project concept 2

Examples and analysis of existing projects for the production of biomethane using lignocellulosic agro feedstock

SECTION 9

This chapter presents the most well-known examples of the use of lignocellulosic feedstock for biogas production. Presented projects demonstrate the significant progress achieved over the last 15 years, starting with the pioneering projects of HoSt, VERBIO, C.F. Nielsen, BioFuel Technology in countries such as Denmark, Germany, the Netherlands, the USA, and in recent years in France and China.

Chernozemen biogas facility, Bulgaria

The Dutch company HoSt operates a 1.5 MW manure-based biogas plant in Bulgaria with a dedicated straw input system[90]. It was the first biogas plant in which large amounts of straw are fed. The 1.5 MWe capacity plant uses around 50,000 tonnes per annum of cow slurry co-digested with maize silage and straw.

The Chernozemen facility consists of a dedicated solid feeding system, a liquid input system consisting of a pump and cutter, two 2,174 m^3 digester tanks, a single 2,174 m^3 post-digester tank, a separator system, after-storage tanks, and a building with a control and heating room, a 1.5 MWe gen-set and a room for the operator.

One of the striking features is the dedicated straw input system **(Fig. 9.1)**. Straw bales are placed on a large straw conveyor that can handle straw bales and feeds the bales to a bale breaker. Here the first initial size reduction takes place before a hammer mill. The hammer mill is sufficient to mill the straw enough to break its tubular structure to prevent floatation. Tests were conducted with different sieve sizes to find the optimal particle size for the digestion process.

Apart from the feeding system, the digester tanks are optimized for the digestion of straw. A special paddle mixing technology combined with propeller mixers ensures that no floating layers are formed.

Demonstration biogas plant in Foulum, Denmark

Another example of the successful use of wheat straw in biogas production is a pilot demonstration project in Foulum, Denmark. The project is a joint

Fig. 9.1 – Straw feeding and pretreatment line (photo by HoSt)


Fig. 9.2 – Straw briquette feeding line

development of the companies C.F. Nielsen, BioFuel Technology and Aarhus University (Denmark). A feature of this project is the demonstration of the possibility and advantages of using the co-digestion of liquid pig manure and briquetted wheat straw.

The demonstration biogas plant was installed and launched to test the technological modes in 2012. A straw briquetting line was launched at the biogas plant **(Fig. 9.2)**. The authors of the project had accumulated data on the effectiveness of the proposed technology, according to which a conclusion was made about the feasibility of co-digestion of manure with briquetted straw. It has been shown that briquetting of straw allows to reduce viscosity of the fermented mass in the reactor, which, in turn, allows mixing the contents of the bioreactor more completely and evenly. The authors noted that there were no problems with mixing the contents of the reactor and crust formation even when the TS concentration raised up to 14%.

In addition, straw briquetting leads to a 35% increase in the specific CH_4 yield (0.277 Nm^3CH_4/kgVS or 235 Nm^3CH_4/t straw), compared to untreated straw[91]. Adding straw to the slurry also significantly reduced the H_2S concentration – from 1900 to 365 ppm.

The energy consumption during briquetting on experimental equipment was about 90 kWh/t straw, although it is noted that industrial scale briquetting could lead to reduction of energy consumption by a half. Separately, the costs of cutting and grinding straw amounted to another about 40 kWh/t straw, which can also be significantly reduced when using energy-efficient industrial equipment.

VERBIO Schwedt biomethane facility, Germany

Verbio's biomethane facility[92, 93, 94] was introduced in 2010 as the world's first large-scale innovative plant for mono-straw fermentation. It is based on the bioethanol refinery in Schwedt (Brandenburg). First stage was commissioned in 2014.


Fig. 9.3 – VERBIO Schwedt biomethane facility

Fig. 9.4 – VERBIO Nevada Biorefinery biomethane plant

The plant was planned for extension to reach 16.5 MW capacity by the year 2019, generating 140 GWh of biomethane annually for sale as biofuel from approximately 40,000 tons of straw. For this purpose, EUR 25 million was invested.

The working volume of the digesters is 8,000 – 10,000 m^3. The feedstock is supplied by the local farmers in exchange for produced organic fertilizer (digestate), thus ensuring 'payment' for the straw. Straw is pre-treated mechanically and thermally. Biomethane is pumped into the local gas grid.

The straw bales used to feed the plant is gathered within a radius of 80 km of the plant to ensure maximum economic and ecological efficiency. In exchange, the fermentation waste is provided to farmers as organic fertilizer. This local production chain is creating employment in the region's agricultural sector and ensure maximum CO_2 efficiency.

VERBIO Nevada Biorefinery biomethane plant, USA

Verbio has been producing renewable natural gas (RNG or biomethane) from corn stover on an industrial scale since December 2021 in Nevada City, Iowa[95, 96, 97, 98, 99]. The project includes a two-phased construction campaign with commissioning the first phase in 2021 and the second in 2022. Total investments amount to $35 million (1st stage) and $80 million (2nd stage). The full annual biomethane production capacity is estimated to be 680 GWh.

The plant consists from 16 fermenters in total, each with a capacity of 10,600 m^3. Main feedstock is baled corn stover in amount of 75,000-100,000 t/a. Pretreatment includes grinding and thermal treatment by hot water. Water is used at elevated temperatures (160-240 °C) and high pressures.

The plant grinds square bales of corn stover purchased from local farmers. Once the bales are put into storage and checked for moisture percentage, the stover is then loaded onto one of two conveyer belt lines and sent through the hammer mill to break up larger pieces, filter those through a screen, add water to it, mix it up and send it to the digesters.

The Nevada plant is built on 55 acres of land and employs a workforce numbering approximately 100 persons. Due to major risks associated with availability of the feedstock for anaerobic digestion, VERBIO Agriculture (VA), LLC (formerly VERBIO Farm Services, LLC) was formed. Its primary responsibilities are to secure feedstock of baled crop residue that is procured within 80 - 120 km radius.

Corn straw biogas plant in Fuyu county, Heilongjiang, China

The biogas plant located in a state-owned farm (Fanrong stock farm, Fuyu county, Qiqihar city, Heilongjiang Province) is the first biogas CHP facility to use pure yellow corn straw as feedstock in the north region of China[100]. The 2MWe facility consumes 30,000 tonnes of corn straw. It was constructed (and is operated) by Nanjing General New Energy Power Co. Ltd. at a total investment cost of 55 million yuan. The project started commissioning in November 2016 and has been running continuously for over 30,000 hours by 2021.

Fig. 9.5 – Corn straw biogas plant in Fuyu county

The straw is first crushed to smaller pieces (less than 3 cm). It is then ensiled in silos where the moisture content is adjusted to about 60% by adding water. Compression is applied layer by layer and straw is covered with films to remove air. This can reduce dry matter loss with typically 80% less loss of dry matter as compared to open storage. During ensiling organic acids are produced, which shorten the required hydraulic retention times in digestion to less than 35 days.

Each fermenter tank has a volume of about 4000 m^3. The total solids concentration in the fermenters is kept in the range from 8 to 10%. A combined mixing using long-shaft mixers, submersible mixers and slurry recirculation improves homogenization and avoids floating straw and crust formation. The biogas yield reaches 320-350 m^3/t DM at a hydraulic retention time of 35 days.

Around 16 GWh of electricity are generated per year. The exhaust heat of the CHP units is used to warm the substrate and maintain a constant temperature in the fermentation tanks. The project reduces carbon dioxide emissions by 17,000 tonnes per year.

Harbin, Heilongjiang | Derun (Wuchang) Biogas Cogeneration Project, China

Construction of the Wuchang project began in August 2019. The project consists of 12 CSTR digesters[101]. It utilized dry straw as feedstock, with a TS of over 80%. The feedstock comprises a mixture of corn and rice straw. The project was implemented in two phases, with a total power generation capacity of 8 MW. The design substrate feeding capacity is 260 tons daily, resulting in a daily biogas production of 80,000 m^3 and a daily power generation 160 MWh.

Fig. 9.6 – Derun (Wuchang) Biogas Cogeneration Project

Fig. 9.7 – Harbin straw biomethane plant

The largest commercial straw biomethane plant ever built, China

The plant was constructed in Harbin in 2022. It utilizes 58,000 t/a of corn stover and 58,000 t/a of rice straw[102, 103]. Sitting on approximately 13 hectares of land, in which half of the space is feedstock storage, it is the world largest biogas plant so far that uses only corn and rice straw as waste input. The installed power capacity of the plant is 30 MW. According to the WABIO, the technology provider, one can expect a productivity rate of up to 600 Nm^3 of biogas per tonne of corn straw on a 65% methane rate. The produced biomethane is further processed to produce bio-CNG. According to the open-source information, total project investments amount to €43 million.

Agri biogenic energy park, Denmark

This energy park includes Danish cooperative biomethane plant, owned by more than 100 private farmers and co-founded by Stiesdal SkyClean. The core concept behind Agri Energy's biogenic energy park involves the use of the Sauter biogas technology, which utilizes primarily straw instead of manure to produce biogas[104, 105, 106, 107].

Biogas plant processes 196,000 tonnes of biomass per year **(Table 9.1)** producing approximately 13 million Nm^3CH_4/year. The biomass consists primarily of residual products from agricultural production, such as straw, beet tops, potato pulp, deep litter and manure. The reactors are fitted with a non-traditional stirring method utilizing spraying nozzles shown in **Fig. 9.8** It is used there due to the high-fibrous nature of the feedstock that would make the application of traditional agitators difficult.

Table 9.1 – Feedstock used for digestion

Raw material	DM content, $\%_{FM}$	Degradation rate, %
Straw	85	52
Cattle slurry	7	46
Deep bedding	30	48
Potato pulp	18	70
Grass	30	70
Beet leaves	17	83

The biogas upgrading is done with an amine scrubber. Produced biomethane is fed into natural gas system. The second phase of the project includes scaling up the plant to process 600,000 tonnes of biomass annually producing nearly 40 million Nm^3CH_4/a.

Biomethane production is integrated with Stiesdal's SkyClean pyrolysis technology. The result is a uniquely efficient utilization of plant carbon in the biomass, as the residual fibers from biogas production are elevated to create two additional value streams: green pyrolysis fuel and biochar for the capture and storage of CO_2.

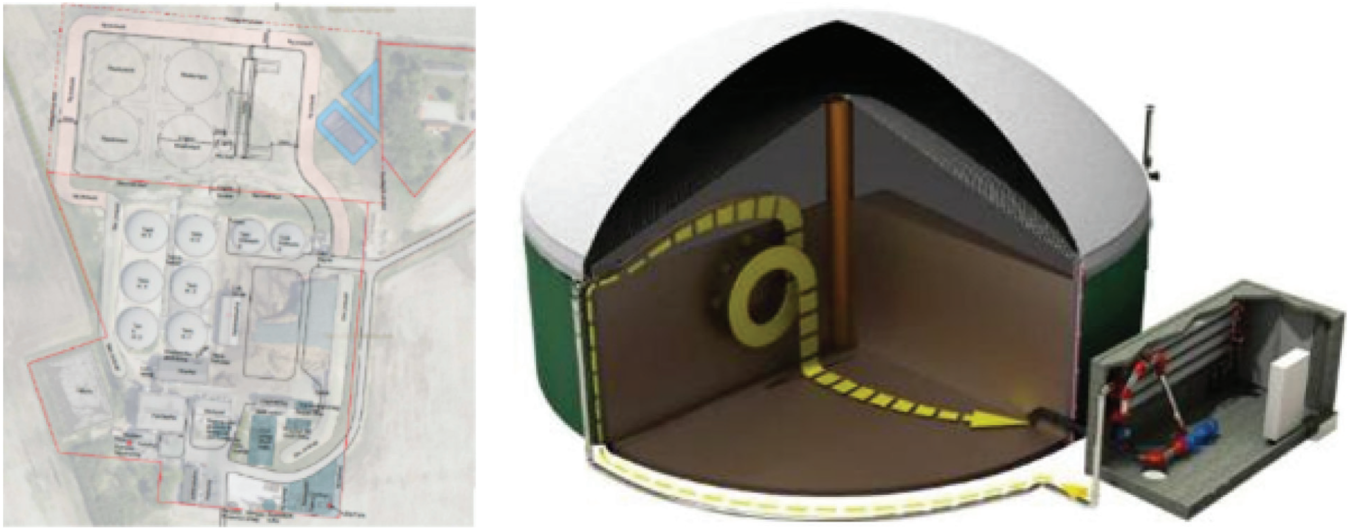


Fig. 9.8 – Agri Energy's biogenic energy park: plant layout (left) and feestock flow principle into a digester and an external heat exchanger (right)

Biogas plant in Kværs, Denmark

A new biogas plant in Kværs **(Fig 9.9)**, Denmark, is a large-scale facility constructed by Nature Energy and is expected to produce RNG (biomethane)[108]. Construction began in 2020 and was completed, with the plant starting production in 2022. The plant can handle 800,000 tonnes of biomass annually and is expected to produce over 20 million m^3 of RNG, displacing natural gas from the Danish energy system.

This project uses Linka Energy and EUROmilling's complete straw handling system. The system includes a thermal and mechanical straw pretreatment plant that breaks down the straw, which is then utilized in the next stage of the biogas plant. The straw is shredded by drums that both cut and separate the straw fibers before they fall into the collection bin. The drums operate at low speed, which reduces energy consumption and lowers the risk of sparking. Next system consists of an EUROmilling grinding setup that handles the shredded straw and includes a pre-mill, a hammer mill, and a pre-mixer.

Biomethane plant Charpentier, France

The Biomethane plant Charpentier in France **(Fig. 9.10)**, located in Chailly-en-Brie, had its construction started in August 2020, and the commissioning of the gas purification unit was realized in June 2021[109]. The project of the biogas plant itself was developed by a French-based company "CPL Biogaz", the fermentation units were erected by the

Fig. 9.9 – Biogas plant in Kværs: general view (left) and LinKa straw pretreatment line (right)

Fig. 9.10 – Biomethane plant Charpentier

French engineering office SAS ASTECA and installation of the entire feedstock supply and fermentation line was made possible by BioConstruct. The commissioning of the biogas upgrading unit was held in 2021 while the plant itself was built in 2020.

The feedstock utilised for biomethane production is primarily agricultural residues and includes sugar beet pulp, cereal waste and some parts of energy crops like rye whole plant silage and maize silage. The total feedstock input represents 17,000 t/a with further conversion to approximately 180 Nm^3CH_4/h (1.57 million Nm^3CH_4/a). The produced biomethane is then fed into the local gas grid.

Alliance Berry Energies Vertes, France

Construction work on the biomethane plant officially began in autumn 2022. This project brings together 51 local farmers in the Luçay le Mâle, France. The feedstock is gathered and supplied in the range of 12 km from the biogas plant in the amount of 80,000 t/a[110, 111]. The primary feedstock is liquid manure and wheat residuals (all the material that comes out of the sieves of a combine harvester including husks, chaff, broken grain, small straws, and weeds). On-site generation of digestate is estimated to be 73,000 t/a.

Biomethane is being produced (620 Nm^3 CH_4/h or 5.4 million Nm^3 CH_4/a) and injected into the local gas grid. Annually the plant saves 13,600 tonnes of CO_2 equivalent. Currently, the project owners are looking into ways of optimizing plant production via the utilization of captured CO_2 (micro-algae cultivation, greenhouses, etc.). Apart from the key basic investments for the biomethane plant, it includes €500,000 invested into air treatment, biofilter and sealing to eliminate any potentially troublesome odors during the operation. Total investments amount to 22 million euros.

Fig. 9.11 – Alliance Berry Energies Vertes biomethane plant: plant layout (left), general view (right)

The use of agricultural residues for biomethane production is a rapidly growing field, driven by a global push for renewable energy, waste management, and climate change mitigation. Information regarding listed above project examples is collected in the **Table 9.2.**

There's a strong emphasis on using agricultural residues (straw, corn stovers, husks, vegetable waste rather than dedicated energy crops that might compete with food production. This aligns with sustainability criteria and circular economy principles.

Table 9.2 – Existing project additional information

Facility/ project name	Feedstock treated in ton/a	Feedstock type	Feedstock (pre)-treatment	CH_4 production, mcm	Project start up	Cost, mill EUR (M€)	Country
Chernozemen	50,000	Cow manure, maize silage, straw	Hammer mill	3.8*	n.a.	n.a.	Bulgaria
Foulum	17,000 (8.5% straw)	Straw, pig manure	Briquetting	>1.7 (biogas)	2012	n.a.	Denmark
VERBIO	40,000	Straw	Mechanical grinding	14	2014	25	Germany
VERBIO	75,000 -100,000	Corn stover	Grinding and thermal treatment by hot water	68	2021	115	USA
Fuyu county	30,000	Yellow corn straw	Crushing (less than 3 cm) and ensiling with organic acids	~ 4.6*	2016	55 mill yuan (~ 7 M€)	China
Harbin 1	95,000	Corn and rice straw	Fermentation (hydrolysis) and agitation	29	2019	n.a.	China
Harbin 2	116,000	Corn and rice straw	Fermentation and agitation	45	2022	43	China
Agri biogenic energy park	196,000	Manure, straw, bedding, grass, potato pulp, leaves	Sauter biogas technology	13	2016	n.a.	Denmark
Kværs	800,000	Manure (?) and straw	Thermal and mechanical grinding of straw	20	2022	n.a.	Denmark
Charpentier	17,000	SBP, cereal residuals and energy crops	Mixing pump including shredding unit	1.6	2021	n.a	France
Alliance Berry	80,000	Manure + wheat residuals	Standard treatment	5.4	2022	22	France

** Calculated based on CHP electricity efficiency 0.35*

Agricultural residues, especially lignocellulosic materials (like straw), are notoriously difficult to degrade. Tendencies include increased research and implementation of pre-treatment methods (physical, chemical, biological, and combined approaches) to break down these complex materials, improve hydrolysis, and significantly increase biomethane yield. The most used approach includes combination of mechanical and thermal treatment.

First pioneering projects have been working in Germany and USA utilizing VERBIO technology solution.

Denmark is a leading country in large cooperative biomethane projects based on agricultural residues. While large, centralized plants can benefit from economies of scale, there's also a recognized need for smaller, on-farm or community-level biogas systems to manage local waste and provide energy directly to farms or small grids. This decentralized approach offers flexibility and reduces transportation costs for feedstock. It is developed in France where small- and mid-size project produce biomethane from mixture of animal waste and plant residuals.

With vast agricultural land and livestock, China has a massive potential for agricultural residue-based biogas. Current projects range from household-scale digesters to large industrial plants in north part of the country for treatment of 100% of corn straw.

Assessment of the potential for biomethane production from crop residues in Ukraine

SECTION 10

Methodology

Estimation of crop residues value is based on the data of the State Statistic Service of Ukraine (SSSU) on production of the main crops at enterprises in 2021. The production of crops at households were not taken into account.

The yields of biomass tied to commodity crops production via corresponding rates given in the **Table 10.1.** The theoretical crop residue yields and technically available parts were used from[112, 113] and methane yield potentials used from[114, 115, 116].

The crop residue yield indicator shows the specific theoretical mass of the plant, which is generated at the time of harvest per unit mass of the target product (grains, roots). The technical potential of the collection takes into account only the part of the plant that can be collected by traditional technical means of collection. The rest of the unharvested mass of the plant actually remains in the field and is plowed. The assessment of the potential use of crop residues for biogas production takes into account the part of collected biomass as given in the **Table 10.1.**

This approach is conservative and takes into account the potential alternative consumption of crop residues (as bedding for livestock farms, substrate for mushrooms growing, building or industrial material, solid renewable fuel, etc.) or their direct application to the fields to replenish humus balance.

However, ultimately the whole mass of collected crop residues can be used for biogas production without any substantial influence for the crop cultivation. It is well known that organic matter is converted via anaerobic digestion process resulting in biogas release composed mainly from methane and carbon dioxide. So, almost whole mass of nutrients and approximately a half of an organic carbon in raw matter is contained in digestate and, as a rule,

Table 10.1 – Parameters used for crop residues

Feedstock type	**Theoretical crop residue yield,** ton raw mass per ton of commodity crop	**Technically available for collection crop residue yield,** % to theoretical crop residue yield	**Share accounted for biogas production,** % to technically available for collection crop residue yield	**Methane yield potential,** Nm^3CH_4/t raw mass
Wheat straw	1	60	33	230
Rye straw	1	60	33	230
Barley straw	0.8	60	33	230
Corn stover	1.3	70	43	140
Sunflower stalks and cobs	1.9	67	40	53
Soybean straw	1	70	43	191
Rape straw	2	70	43	135
Sugar beet tops	0.45	90	100	38

is returned to the fields in the converted forms ready to use by plants. Using this approach will give even higher biomethane production potential from crop residues – up to 12.9 billion m^3 CH_4 per year.

The estimated biomethane potential was further multiplied by the predicted growth factors by 2050 for each considered crop. Growth factor of 1.2 was applied for wheat, barley and rye, 1.25 – for corn, and 1.0 – for the rest crops.

The approximation of crop production in the districts marked SSSU as confidential was done based on the following approach. From the known total volume of commodity crops in the entire region (oblast) were subtracted the sum of the known volume of commodity crops in the districts and further the rest was redistributed between the rest of districts in proportion to sown area in the districts.

Biomethane potential

National level

The estimated biomethane potential from the crop residues amounts to 5.2 bcm (billion Nm^3CH_4) per year. Significant part of the potential is related to corn stover (48.0%) and wheat straw (27.3%) **(Fig. 10.1).**

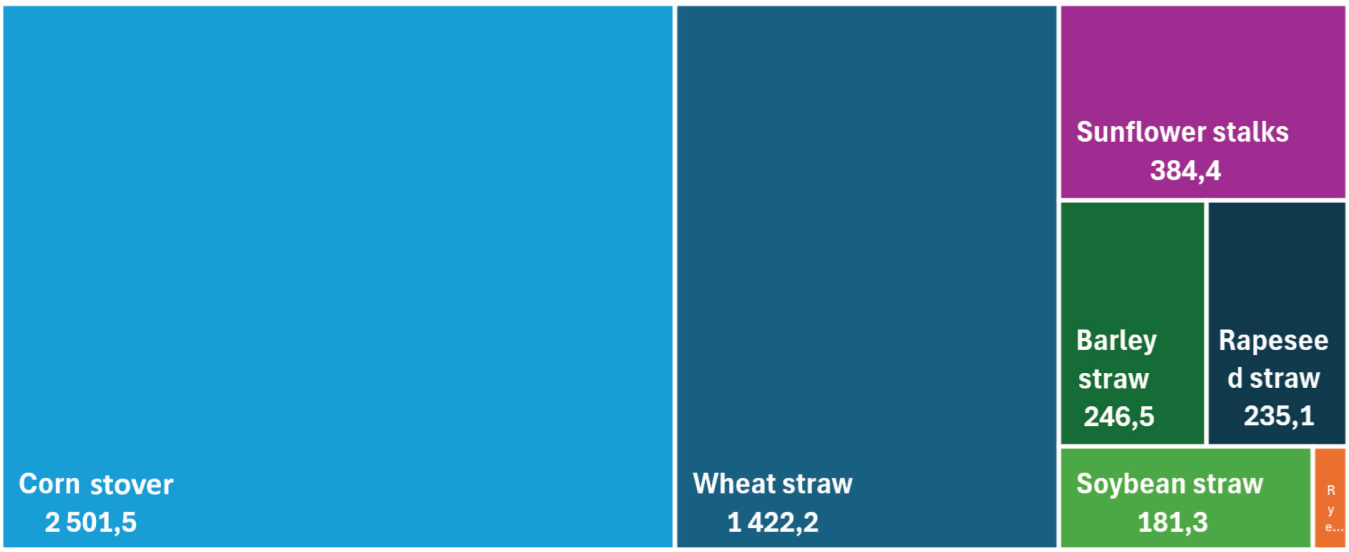


Fig. 10.1 – The structure of biomethane production potential from crop residues in Ukraine (mln Nm^3CH_4/yr)

Regional level

On the regional level biomethane potential from crop residues is available in each region in the range from 10 to 447 mln Nm^3CH_4/yr **(Table 10.2).** but is the most concentrated in central and Northen parts on Ukraine, while the least concentrated in Western part of Ukraine **(Fig. 10.2).**

Table 10.2 – The level of biomethane potential from crop residues available in each region

Region	Biomethane potential, mln Nm^3CH_4/yr		
	Wheat straw	Corn stover	Crops residues, total
TOTAL	**1 422.2**	**2 501.5**	**5 214.8**
AR Crimea	n.d.	n.d.	n.d.
Vinnytsya oblast	81.8	261.6	447.1
Volynska oblast	26.1	33.1	96.7
Dnipropetrovska obl.	116.9	55.1	241.8
Donetska oblast	72.8	5.1	102.8
Zhytomyrska oblast	35.6	146.1	232.4
Zakarpatska oblast	0.7	7.6	10.4
Zaporizka oblast	111.2	16.4	187.3
Ivano-Frankivska oblast	7.3	35.6	60.7
Kyivska oblast	50.2	204.6	320.2
Kirovohradska oblast	85.9	136.6	291.0
Luhanska oblast	51.7	6.8	80.5
Lvivska oblast	26.8	48.9	132.8
Mykolaivska oblast	96.7	22.4	188.0
Odeska oblast	108.8	37.8	240.5
Poltavska oblast	54.8	256.8	377.6
Rivnenska oblast	18.0	58.4	113.5
Sumska oblast	45.6	204.4	289.3
Ternopilska oblast	46.1	111.4	227.8
Kharkiv oblast	135.2	71.1	259.6
Kherson oblast	77.8	27.6	172.6
Khmelnytskiy oblast	64.2	202.0	369.5
Cherkasy oblast	54.9	225.2	331.4
Chernivtsi oblast	6.4	11.0	27.5
Chernihiv oblast	47.0	315.9	414.0

Notes: n.d. – no data

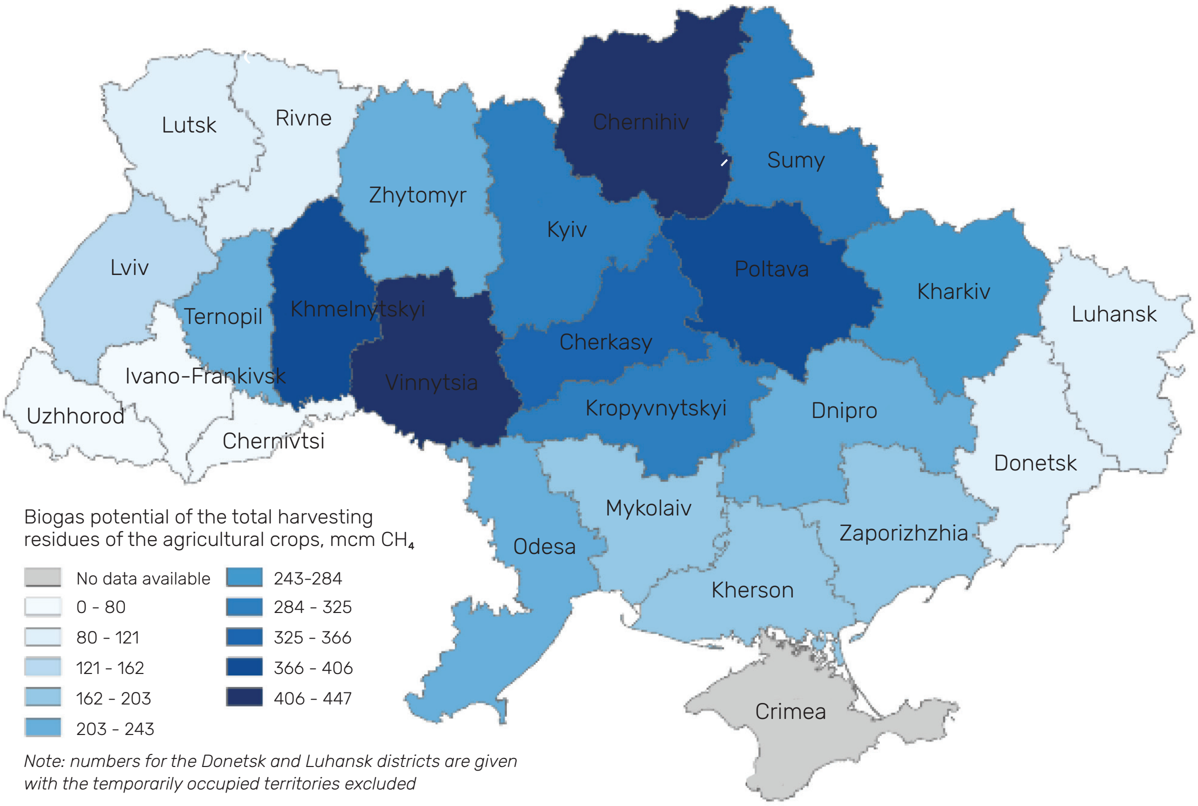


Fig. 10.2 – Biogas/biomethane potential of crop residues in mln Nm^3CH_4 per year (oblast level)

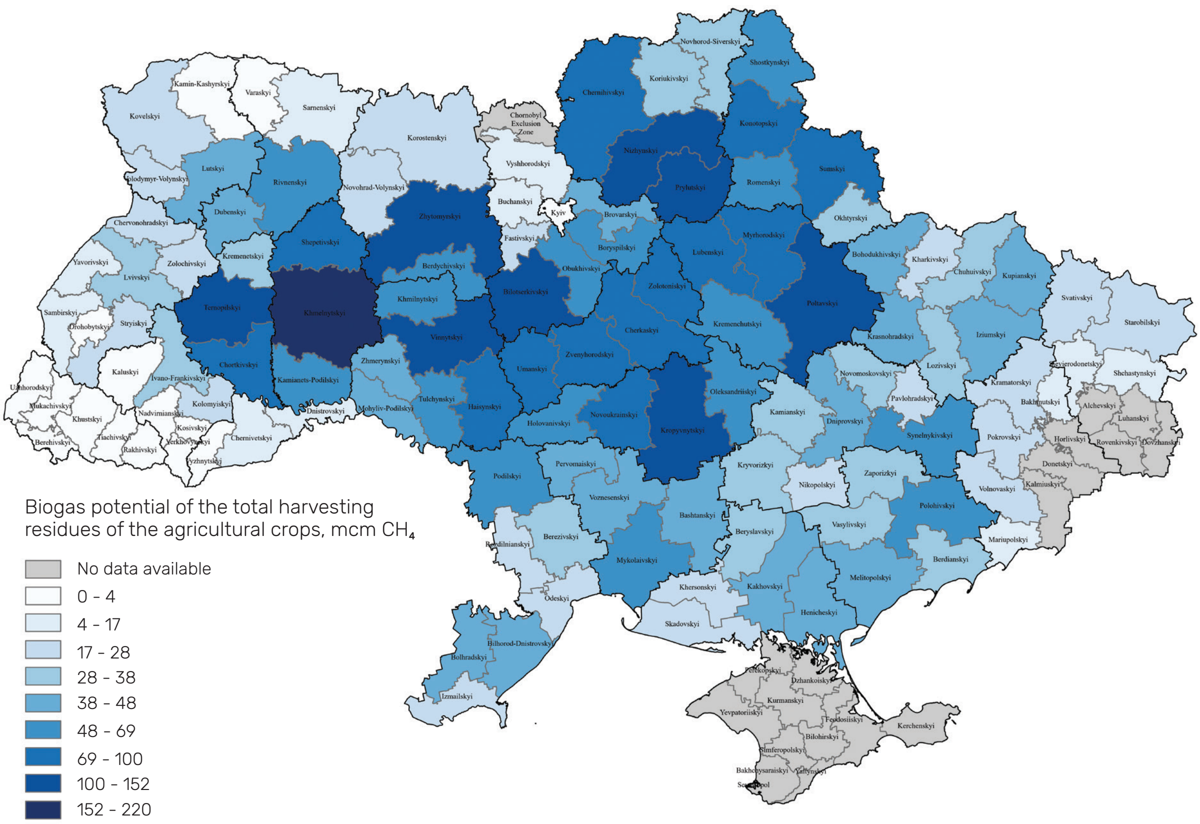


Fig. 10.3 – Biogas/biomethane potential of crop residues in mln Nm^3CH_4 per year CH_4 (district level)

District level

The distribution of biomethane potential from crop residues over districts of Ukraine is shown in the **Fig. 10.3.**

Conclusions and recommendations

Crop residues together with animal manure are the largest sources of feedstock for all regions in the world, particularly in developing economies where the agricultural sector often plays a prominent role in the economy. In European countries, the contribution of crop residues to the total production of biogas and biomethane in 2023 was about 30%, and is the largest among other types of feedstock. According to the forecast of the European Biogas Association, the potential for biogas energy production from agricultural residues will total 20%, and is second only to the potential for biogas from cover/intermediate crops.

Lignocellulosic types of crop residues can become a significant source of feedstock for biomethane production in Ukraine as well, with a potential of 5.2 million m^3CH_4/year, the lion's share of which belongs to wheat straw and corn stover (about 75%). Such raw materials can be collected in all the regions of Ukraine, although the concentration of potential is greater in the central and northern regions.

Existing technologies and equipment for harvesting crop residues allow for the technical collection of such biomass from the fields. However, recently in Ukraine, wheat straw is mainly harvested, less often soybean and rapeseed straw, as well as corn stover. A feature of harvesting corn stover as raw material for a biogas plant is its relatively high humidity and unpredictability, depending on weather conditions during harvesting in the autumn period.

Among the main types of crop residues, potentially the most available for biogas production is corn stover, as well as soybean straw, rapeseed straw and sunflower stalks. Wheat straw, due to its rather high competitive demand in a number of other areas, may be a limited resource at the level of individual farms or districts.

The main features of crop residues as raw materials for biogas production are high dry matter content, non-optimal C:N ratio for anaerobic digestion, relatively high lignin and lignocellulosic complexes content, low wettability and low bulk density in the uncompacted state.

There are a number of physical, chemical, biological and combined methods of pre-treatment of lignocellulosic raw materials, such as straw or corn stover. All methods allow to increase the bioavailability of cellulose to varying degrees and increase the specific yield of methane. Some methods also allow to decompose lignin, but may lead to the formation of substances that inhibit the anaerobic digestion process, for example, furfural. Most methods allow to obtain more energy in the additionally produced biomethane than is consumed.

Commercially available technologies and equipment for pre-treatment of lignocellulosic types of agricultural raw materials are represented mainly by mechanical hammer or knife crushers, extruders, cavitation or steam-explosion facilities. One of the commercially available solutions for straw pretreatment before anaerobic digestion is also the use of market-quality pellets production line. There are also examples of specialized production of energy pellets for biogas with increased methane yield.

After appropriate pre-treatment, crop residues can be used as raw material for biogas production in almost any existing configuration of biogas plants. The most common solution for processing agricultural raw materials and waste, including crop residues, are technological schemes based on continuous stirred tank reactors (CSTR). The use of other types of anaerobic bioreactors is also possible, but is not yet a common solution and will require appropriate justification.

The use of crop residues for the production of biogas and biomethane, provided that the digestate is returned to the fields from which such biomass was collected, is a sound and justified solution, both from an agronomic, environmental and energy point of view. Such an approach will not lead to soil depletion and increased greenhouse gas emissions into the atmosphere.

The diesel energy consumption for the collecting and logistics of crop residues to the biogas plant, also taking into account the consumption for growing, collecting and logistics operations of corn silage, which is used to meet the biomethane complex's own energy needs, are only 3.3-4.9% of the energy of the produced biomethane. When consuming electricity from the network, the share of energy consumption for the production of biomethane can increase up to 25%.

Economic analysis has shown that biomethane production from crop residues can be profitable with an IRR of 21%, provided that manure is used as additional feedstock (5.2 ton manure with TS content 4% per 1 ton of mixture of straw and corn stover), own energy needs are ensured by biogas from corn silage, and utilization CO_2 from biogas upgrading, However, such a project will be quite sensitive to changes in the price of biomethane and the cost of raw material.

It is also shown that the production of biomethane from granulated straw and corn stover, provided that the granulation line is a part of the biomethane project as a pre-treatment unit, is comparable in profitability to the production of biomethane from straw and corn stover pretreated with bioextruder.

The use of crop residues is becoming widespread in the world. Biogas and biomethane projects are being built both in European countries and in Asian countries, in particular in China. There is also a project to produce biomethane from corn stover in the USA. Straw and corn stover are used as raw materials for the production of biogas and biomethane in projects with a capacity of 1 to more than 68 million m^3CH_4 per year.

Resuming, we can say that crop residues are reasonable to be considered as raw materials for the production of biomethane in Ukraine, provided that biomethane is sold on the market of renewable biofuels in European countries. A strategy to increase the economic sustainability of the project may be to guarantee an acceptable price for the produced biomethane at a level of no lower than 90 euros/MWh and to find sales markets or consumption of CO_2 from biogas upgrading with a price at least 110 euros/t, excluding VAT.

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