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Feasibility study and carbon footprint assessment of biomethane production from intermediate crops in Ukraine

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ABSTRACT

The growing production and consumption of biomethane are among the prevailing trends in European bioenergy. Biomethane is a close analogue of natural gas, so it can be used for the production of heat and power as well as consumed as a motor fuel and raw material for the chemical industry. Biomethane production is in line with the concept of a circular economy, since it converts agricultural by-products and residues, as well as industrial and household wastes, into energy, at the same time ensuring the recycling of nutrients back to agricultural land. The application of biomethane to replace fossil fuels requires minimal additional resources and time to develop new infrastructure or adjust the existing one. This makes biomethane a key player in the transition towards a climate-neutral economy. Expanding production of biomethane requires new sources of sustainable feedstock. Sequential cropping offers an opportunity to produce sustainable biomass for energy, reducing greenhouse gas (GHG) emissions and avoiding competition with food production. Available studies show that the potential of biomethane production from intermediate crops in Europe is about 45 billion m^3/y. In Ukraine, up to now, intermediate crops have been grown in limited areas for use as green manure or for feed production. Spreading the area under such crops and integrating the biomass into biomethane value chains, with nutrients returned to the soil through digestate, is a new perspective for sustainable bioenergy and agriculture. The assessed potential for biomethane production from intermediate crops in Ukraine is more than 9 billion m^3/y. A feasibility study of biomethane production from such crops shows sufficient attractiveness of the relevant project for investments, with a discounted payback period of 7.8 years and a 20% internal return rate. The averaged emissions during the biomethane life cycle could be negative, provided the carbon dioxide obtained from biogas upgrading is usefully utilised to replace carbon dioxide obtained from fossil fuels. The GHG emissions for biomethane from intermediate crops might reach –13 gCO_{2eq}/MJ when intermediate crops are co-digested with manure, and 25% of the total biomethane comes from this feedstock.

Keywords: bioenergy, biomass, biogas, biomethane, intermediate crops, cover crops, carbon footprint.

INTRODUCTION

Bioenergy has established itself as an integral part of the world's energy sector, providing more than 10% (> 56 EJ/y) of the global primary energy supply, which is about 70% of the total renewable energy supply. By 2050, the contribution of bioenergy is expected to be 64 to 313 EJ/y or 7.5–37% of the global primary energy supply (Errera et al. 2023). The International Renewable Energy Agency, under its "1.5°C scenario", assesses that energy production from biomass will triple by 2050 and reach 153 EJ/year in the world (IRENA, 2022). The widespread use of modern bioenergy technologies, as opposed to the inefficient traditional use of solid biomass, will be crucial for the global energy transition towards net-zero carbon emissions. The share of bioenergy in the EU's final energy consumption is nearly 13%, which allows annual avoidance of 300 Mt CO_{2eq} of greenhouse gas (GHG) emissions. Biomass remains the largest renewable energy source in the EU, providing about 55% of the total renewable energy production. Earlier, this share was about 70%; its gradual decrease is explained by the active development of wind energy, solar energy, and heat pumps in Europe.

One of the current prevailing tendencies in the European bioenergy sector is the growing production and consumption of biomethane. This energy carrier possesses properties similar to those of natural gas, which is why it is a versatile gaseous biofuel with possible applications in many sectors (Marconi and Rosa, 2023). In Europe in 2023, 23% of the upgraded biogas was used for transport, 17% for residential heating, 15% for power production, and 13% for industry. The consumption of biomethane in transport dominates in Finland, Estonia, Italy (100% of the total), Sweden, and Norway (70–80%). The United Kingdom and Switzerland use biomethane mainly for residential heating (50–60%), while Belgium predominantly for industrial needs (80%).

The annual production of biomethane in Europe grew to 4.9 billion cubic metres (bcm) in 2023, the installed capacity of the plants being 6.4 bcm/y by the first quarter of 2024. The major part of biomethane (69%) is produced from agricultural biomass, followed by organic municipal solid waste (11%), waste of the food industry (9%), and some other feedstocks (EBA, 2024). European REPowerEU Plan envisages boosting sustainable biomethane production to 35 bcm by 2030 as a cost-efficient way to decrease imports of natural gas (Siddi, 2022). The priority focus is on obtaining biomethane from waste and residues to avoid competition with food and feed production.

According to the European Biogas Association (EBA, 2024), Europe could potentially produce 40 bcm/y of biomethane by 2030 and 111 bcm/y by 2040, of which 101 bcm/y will relate to the EU. The production of biomethane in the EU in 2040 is expected to be via anaerobic digestion (67% of the total) as well as via thermal gasification of solid biomass (33%). With regard to anaerobic digestion, the prevailing feedstocks are predicted to be intermediate crops (43% of the total), agricultural residues (20%), and livestock manure (19%). Potential leaders in utilizing intermediate crops for biomethane production will be Spain, France, Italy, Germany, and Poland, with 3–5.5 bcm/y (Alberici et al., 2023).

Intermediate crops (other names can be sequential or cover crops) are a relatively new type of feedstock for biogas/biomethane in Europe. Agricultural crops can be divided into two big categories: main and intermediate. Main crops occupy the field for most of the growing season. After they are harvested, it is often possible to cultivate other crops to obtain additional products, provided that there is enough moisture in the soil. Intermediate crops are grown in the time interval free from the cultivation of main crops in crop rotations. Sequential cropping allows obtaining two yields from the same area during a year, and irrigated lands might give even three harvests.

When growing two crops, the field is occupied by plants from early spring to late autumn; when growing winter intermediate crops, the field is occupied by plants also in winter. The constant presence of the plant cover has a positive effect on the physical properties of the soil, the migration of salts in it, and the microclimate of the surface layer. Intermediate crops planted between main (cash) crop cycles protect soil from erosion, suppress weeds, and add organic matter to the soil when they decompose (Pandey, 2024). Intermediate crops that are grown specifically for incorporation into the soil as fertilizer are called green manure. They are usually fast-growing and include species such as legumes (Meena et al., 2018).

The concept of using intermediate crops for biogas/biomethane with the return of digestate to the field is reflected in the Biogasdoneright™ model. The model developed in Italy (Dale et al., 2016) suggested a new system for the sustainable production of food, feed, and biogas. Its core is that the main agricultural crops are used only for food or feed, while the biomass of intermediate crops can be consumed for biogas/biomethane, with digestate from the biogas plant applied as organic fertilizer. The Biogasdoneright™ model has already been applied on more than 600 farms in Italy and France, while intensive pilot studies of the model have been conducted in the USA (Magnolo et al., 2021; Selvaggi et al., 2018). A positive influence on the organic carbon stock in the soil from returning digestate of intermediate crops has been proved by modelling (Launay et al., 2022; Marsac et al., 2019) and field studies (Levavasseur et al., 2023; Szerencsits et al., 2015).

According to the study results (Magnolo et al., 2021), the potential for biomethane production from intermediate crops ranges from 46 bcm/y (the conservative scenario) to 185 bcm/y (the maximum scenario) in Europe. In relation to different climatic regions of Europe, the highest potential is in countries of the Continental region:

nearly 26 bcm/y by the conservative scenario and 105 bcm/y by the maximum scenario. In the conservative scenario, the area of land suitable for intermediate cropping is assumed as 20% of the total area under main crops. In the maximum scenario, which in fact represents the theoretical potential, this figure is 80%.

Biomethane Industrial Partnership (BIP, 2025) has made a step forward, suggesting novel crop rotations and a new approach to modelling biomethane potential. The intermediate crop is introduced as an additional crop into the existing crop rotation during periods where the land is usually unoccupied between two main crops. Rotational crops are defined as crops cultivated within a long (5+ year) crop rotation, which is in line with sustainable growth principles. The deliverable potential and maximum potential for biomethane production based on intermediate cropping across Europe are assessed at 44 bcm/y and 87 bcm/y, respectively. Thus, representing a big source of sustainable biomass in terms of GHG emissions, intermediate crops could considerably expand the feedstock base for biogas and biomethane.

Considering favourable conditions, the production of biomethane in Ukraine is expected to reach 250 million cubic metres (mcm) by 2027, the most optimistic projection being 1 bcm by 2030. This ambitious goal hinges on the cessation of the military invasion in Ukraine, underscoring the importance of a peaceful environment for economic growth. Biomethane is believed to become a significant export commodity for Ukraine's trade with European countries. Exporting biomethane from Ukraine to the EU will contribute to realizing the REPowerEU Plan aimed at reaching the production of 35 bcm CH_4 by 2030 to cut down imports of natural gas. Growing share of biomethane from intermediate crops in Ukraine's exports to the EU is in line with EBA's prediction on the domination of intermediate crops as feedstock for biomethane in Europe in 2040.

The main objectives of the work are to conduct techno-economic assessment and carbon footprint assessment of biomethane production from intermediate crops, as well as to evaluate the feasibility and sustainability of respective projects in Ukraine. These assessments are supplemented by the estimation of the potential for biomethane production from intermediate crops in the country.

MATERIALS AND METHODS

Biogas and biomethane are the focus of this study as their production represents the most dynamically developing sector of Ukraine's bioenergy, with notable achievements and big prospects. The production of biomethane was launched in Ukraine in 2023. Several Ukrainian companies are now producing biomethane and have even started their trial export to Europe in 2025. During the last 20 years, about 90 biogas plants have been built in Ukraine. Recently, the typical capacity range for biogas and biomethane plants has been 1 to 10 mcm of CH_4 a year, which is equivalent to about 0.5–5.0 MW_{el}. The main types of utilized feedstock include livestock and poultry manure, maize silage and sugar beet pulp. In 2022, more than 2 Mt of feedstocks (by raw mass) were consumed to produce biogas in Ukraine. Of the feedstocks, 51% was industrial wastes, mainly sugar beet pulp, while agricultural residues along with energy crops contributed 46% (this estimation does not cover landfill gas from municipal solid waste).

There are different technologies for the production of biogas and biomethane. In the context of the article, anaerobic digestion is considered for biogas and the upgrading of biogas for biomethane. Biogas is a mixture of gases formed as a result of anaerobic methane fermentation of the substrate and consists of methane (55–75%), carbon dioxide (25–45%), hydrogen sulphide, ammonia, and some other gases. The feedstock for biogas production by anaerobic digestion can be any biomass containing a sufficient proportion of biodegradable organic matter. Agricultural feedstocks suitable for biogas production include livestock manure, energy crops (usually maize silage), intermediate crops (rye, triticale, amaranth, etc), as well as crop residues (straw, maize stalks, etc).

In practice, mixtures of different feedstocks are usually used, while mono-fermentation of one feedstock type is fairly rare. This is because practically none of the feedstocks contain a sufficient amount of macro- and microelements necessary for the biological process, or their ratio is not optimal. For agricultural biogas plants, as a rule, only various agricultural feedstocks are combined, with the addition of several by-products of the food industry, such as sugar beet pulp, molasses, distillery stillage, fruit and vegetable pomace, etc. One of the main indicators for an effective fermentation process is the C:N ratio, which is recommended to be within 15–30. The C:N ratio for manure is usually lower (4–15) than the recommended range, while it is usually higher (30–100) for plant-based feedstocks. Combining different types of biomass allows balancing the composition of the mixture.

There are two main approaches to cover energy needs when producing biomethane by means of biogas upgrading. The first one lies in the partial use of biogas for heat and power production. The second approach envisages power supply from the grid and heat from a solid biomass boiler plant. Both options can also include a unit for CO_2 cleaning and liquefaction if it is economically justified. This study employs the first option. Biomethane is obtained through biogas upgrading, which involves removing impurities such as carbon dioxide CO_2 and hydrogen sulphide H_2S. The applied processes, according to the physical principles of their implementation, can be conditionally divided into adsorption, absorption, membrane, cryogenic, and biological ones. For Ukraine's conditions, pressure swing adsorption and membrane separation may be suitable for biogas upgrading due to no need for water and chemicals, the possibility for application at small biogas plants, as well as the prospect for further improvement of these technologies.

The calculation of GHG emission reductions for the biomethane project considered in this study has been carried out based on RED III provisions, in particular, the respective methodology for biomass fuels. A combination of estimated values and disaggregated default values has been applied for the calculation, which is one of the allowed approaches. The disaggregated default values have been partially used for manure and maize silage as components of the feedstock mixture intended for biomethane production. The estimated values have been applied to two types of intermediate crops, which are other components of the feedstock mixture.

Total GHG emissions associated with the production of biomethane (E, g CO_{2eq}/MJ biomethane) can be estimated according to the equation:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \quad (1)$$

where: e_{ec} – emissions from the extraction or cultivation of feedstocks; e_l – annual emissions from carbon stock changes caused by land use change; e_p – emissions from the production of the final product (feedstock processing); e_{td} – emissions from the transportation and distribution of the final product; e_u – emissions from the use of the final product; e_{sca} – emission savings from soil carbon accumulation due to improved agricultural management; e_{ccs} – emission savings from CO_2 capture and geological storage; e_{ccr} – emission savings from CO_2 capture and replacement.

In the case of co-digestion of different feedstocks, the share of each biomass type must be taken into account according to the following equations. For the typical and default values of GHG emissions:

$$E = \sum_1^n S_n \times E_n \quad (2)$$

where: E – GHG emissions per MJ biomethane produced from co-digestion of the defined mixture of substrates; S_n – share of feedstock n in energy content; E_n – emission in g CO_2/MJ for pathway n as provided in Part D of Annex VI of RED III.

For actual GHG emissions:

$$E = \sum_1^n S_n \times (e_{ec,n} + e_{td,feedstock,n} + e_{l,n} - e_{sca,n}) + + e_p + e_{td,product} + e_u - e_{ccs} - e_{ccr} \quad (3)$$

where: E – total emissions associated with the production of biomethane before energy conversion, g CO_{2eq}/MJ biomethane; S_n – share of feedstock n as the fraction of input into digester; $e_{ec,n}$ – emissions from the extraction or cultivation of feedstock n; $e_{td,feedstock,n}$ – emissions from the transportation of feedstock n to digester; $e_{l,n}$ – annual emissions from carbon stock changes caused by land use change, related to feedstock n; $e_{sca,n}$ – emission savings from improved management of feedstock n; $e_{td,product}$ – emissions from the transportation and distribution of biomethane as the final product; e_p, e_u, e_{ccs}, e_{ccr} – the same as in Equation 1.

The values of components $e_{l,n}$ and e_{ccs} of Equation 3 are considered zero as they are not applicable to the conditions of the biomethane project studied in this work. For manure as feedstock for biomethane, a bonus of 45 g CO_{2eq}/MJ manure has been used for improved agricultural and manure management (e_{sca}) according to RED III provisions.

RESULTS AND DISCUSSION

Biomethane potential assessment

In Ukraine, the potential for biomethane production from intermediate crops is estimated at about 9.2 bcm CH_4/y, which is equal to nearly 7.9 Mtoe/y (Table 1). This conservative assessment is based on the assumption that 20% of the sown area is allocated for growing intermediate crops with an average yield of 5 t dry matter (d.m.) per hectare. The assumed biogas yield from the crops is 570 m^3/t d.m. The highest potential of intermediate crops is located in regions with large sown areas, which are mostly situated in the centre and the East of Ukraine. At the same time, a large yield of biomethane per hectare (specific yield) can be reached in the western regions of the country, where precipitation levels are higher. This agrees with the results of the study (Belova et al., 2024), where it is pointed out that western regions of Ukraine have more favourable conditions for growing intermediate crops and cover crops.

The performed estimation shows that intermediate crops have the largest potential (52%) for biomethane production by anaerobic digestion among different feedstock types in Ukraine. Other major parts of this potential are biomethane from primary agricultural residues (3.03 Mtoe/y, about 20% of the total) and biomethane from maize silage grown as an energy crop on unused agricultural land (2.57 Mtoe/y, 17%) (Figure 1). The estimated potential of biomethane obtained via anaerobic digestion can be supplemented by another part produced through thermochemical gasification of biomass. In the study (Geletukha et al., 2025), the potential of biomethane obtained from the gasification of lignocellulosic biomass, such as wood and energy crops, is assessed at 0.82 Mtoe/y, and the potential of biomethane from intermediate crops is the same, 7.89 Mtoe/y.

According to studies (Kotsiuba, 2023; Bohushenko et al., 2024; Dixigroup, 2024), the potential for biomethane production from intermediate (cover) crops in Ukraine is 9.8 bcm/y, which is very close to the results of the present work. Ukraine's focus on biomethane based on European approaches, including the use of cover crops as feedstock, is highlighted in (Okhota, 2023; Golz, 2023).

Ukraine as a country of an eastern continental climate, is mentioned in the study (BIP, 2025) in the context of the possibility for intermediate crop cultivation. Other countries included in this climate category are Bulgaria, Romania, and Slovenia. For the countries of continental climate, it is suggested growing post-harvest or winter intermediate crops for biogas. Also, it is recommended to cultivate nitrogen-fixing cover crops to improve soil fertility. These approaches align with the basic assumptions used in the present study. As the assessment (BIP, 2025) presents results only for the EU countries, the closest comparison with Ukraine can be made with Romania. The sown area in Ukraine is

Table 1. The potential for biomethane production in Ukraine, 2023

Type of feedstock for biomethane	Theoretical potential (TP), bcm CH_4/y	Economic potential available for energy	
		Share of the TP, %	Mtoe/y
Manure of livestock and poultry	0.97	81	0.67
Agricultural residues:	12.83	28	3.03
straw of spiked grain crops	4.57	20	0.78
maize stalks and cobs	4.92	30	1.26
sunflower stalks and heads	1.12	27	0.26
soybean straw	0.81	30	0.21
rapeseed straw	1.12	30	0.29
sugar beet tops	0.29	90	0.22
Food processing industry by-products	2.21	38	0.72
Municipal solid waste	0.56	75	0.36
Sewage sludge from public treatment facilities	0.06	100	0.05
Silage of maize as an energy crop	3.00	100	2.57
Intermediate crops	9.23	100	7.89
Biomethane, total	28.85	62	15.28

about 28 Mha, which is about three times larger than in Romania (9 Mha). Taking into account this difference and some other agricultural and economic distinctions of the two countries, the assessed potential of biomethane production from intermediate crops in Romania (3.6 bcm/y) is comparable with that of Ukraine (9.2 bcm/y) when scaling up respectively.

Feasibility study

The technical and economic assessment of a project on biomethane production from intermediate crops is based on the following concept. This concept is designed to provide good enough economic and ecological indicators of the project, considering sustainability issues. It is assumed that the feedstock is supplied by an agricultural enterprise that owns 10.000 ha of land within one management district; the enterprise also owns a pig farm with an average livestock of 18.000 heads. According to the project concept, 20% of the land (2000 ha) is allocated for growing intermediate crops. At that, the allocated area is divided between the post-harvest vetch-oat mixture (1000 ha) and winter rye (another 1000 ha). These types of intermediate crops have been selected for the feasibility study because they are suitable for the soil, agricultural, and climatic conditions of Ukraine as a whole (Geletukha et al., 2025). When carrying out a feasibility study at the regional level, the types of intermediate crops should be specified, as the best crops and practices may vary depending on local climatic and soil conditions.

The yield of intermediate crops is taken at 4 t d.m./ha for the green mass of the vetch-oat mixture and 8 t d.m./ha for the green mass of winter rye. These values are equal to 13.3 t/ha and 26.7 t/ha of 70% moisture content biomass of the crops. Provided the assumed yield of the intermediate crops, their production amounts to 40 kt/y, which includes about 27 kt of winter rye and 13 kt of the vetch-oat mixture. Other components of the entire feedstock mixture are pig manure (90 kt/y) and maize silage (14 kt/y). Biogas produced from maize silage is intended to be combusted in a cogeneration plant to cover the energy needs of the entire biomethane complex.

It is envisaged that the rye silage, vetch-oat mixture silage, and maize silage will be supplied by a separate division of the agricultural company at a price that considers profitability at 25%. Expenditures for ensiling and supplying silage from the silo to the biogas plant are also included in the project capital and operating costs. The digestate from the biogas plant is expected to be applied to the feedstock producer's fields for the main crops. Taking into account the average application rate of nitrogen, 80–120 kgN/ha, the required sown area for fertilization by digestate is 1780–2670 ha, which is 18–27% of the agricultural enterprise's lands. Though the expenses for transporting and spreading digestate are not included in the feasibility study, this is an important practical issue that should be well elaborated when developing actual biomethane projects.

The construction of the biogas plant of agrarian type comprises main fermenters and a fermenter for post-digestion. The total production of biogas from the feedstock mixture is nearly 10.5 mcm/y with 57% CH_4 concentration (Table 2). The main part of biogas (about 7.7 mcm/y) is fed

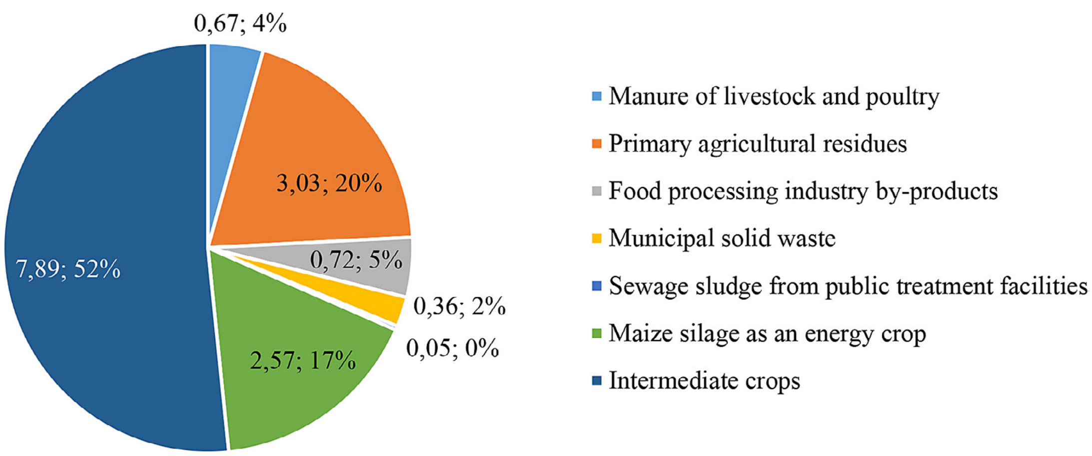

Figure 1. Structure of the biomethane production potential in Ukraine, Mtoe, 2023

into an installation where the biogas is cleaned and upgraded to biomethane quality using membrane technology. This technology has been selected for the feasibility study as it offers several key advantages. It eliminates the need for liquids and chemical reagents, features compact equipment design, and balances capital and operating expenditures favourably. Membrane separation also ensures high purity of the resulting biomethane while maintaining low methane losses in the off-gas stream.

According to the project concept, carbon dioxide released during the biogas upgrading process is cleaned and liquefied to be sold as a by-product. It is also envisaged that a boiler plant on agricultural biomass pellets will supply heat to bioreactors during their biological start-up and serve as a standby installation in case the biogas cogeneration plant is not operational. The produced biomethane is intended to be supplied to Ukraine's gas-transport system, with its guarantees of origin sold on the market of renewable biofuels in Europe. The liquefied carbon dioxide will be sold on Ukraine's market, while the digestate applied as fertiliser on the feedstock supplier's fields.

The evaluated capital costs of the biomethane project are 14.2 million EUR, which includes value-added tax (VAT) and customs duties. At that, the biogas production unit requires the lion's share of the investments (43.4%). The specific capital costs of this unit amount to 2185 EUR per kW of the equivalent electrical capacity of the biogas cogeneration unit. This value aligns with the existing average market price for installations of a similar capacity range. Other large parts of investment relate to the biogas upgrading complex (16.2%), the CO_2 liquefaction complex (10.4%), and the ensiling unit (11.4%). The total operating costs are assessed at 2.36 million EUR/y (including VAT), which is 16.6% of the capital expenditure (CAPEX). The main parts of operational expenditure (OPEX) are connected with the purchase, supply, and transportation of feedstock (61.7% in total).

The revenue generated by the project (4.9 million EUR/y without VAT) arises from the sale of biomethane (43.6 GWh/y), liquefied carbon dioxide (5.6 kt/y), and digestate (128.2 kt/y). Under the assumed sale prices, the lion's share of the revenue (nearly 81%) comes from the sale of biomethane, the rest being associated with the sale of CO_2 (15.4%) and digestate (just 4%). The feasibility study of the biomethane project results in the main financial indicators presented in Table 3. The simple payback period is less than 6 years, and the discounted payback period is less than 7.8 years with a nearly 20% internal

Table 2. Characteristics of the feedstocks and indicators for biogas yield used in the feasibility study

Indicator	Unit	The entire mixture	Feedstock			
			Winter rye silage	Pig manure	vetch-oat mixture silage (30%/70%)	Maize silage
Feedstock consumption	t/y	141 614	25 067	90 000	12 533	14 014
Dry matter (DM)	%	14.0	30.0	4.0	30.0	35.0
Dry organic matter (DOM)	% DM	–	90.0	85	90.0	93.5
Total nitrogen content	kg N/t	3.7	5.4	2.8	6.2	4.5
C:N ratio	–	16.6	25.6	5.7	21.6	34.4
Assumed biochemical potential of methane yield	nm^3 CH_4/t DOM	328.6	340.0	360.0	340.0	350.0
	nm^3 CH_4/t	114.6	93.8	12.2	93.8	113.9
Biogas yield	nm^3/t DOM	581.3	618.2	553.8	618.2	636.4
Efficiency	%	95.0	95	95	95	95
Production of biogas	nm^3/day	28 664	11 132	4 411	5 566	7 555
	nm^3/y	10 462 181	4 063 042	1 610 031	2 031 440	2 757 669
Biogas composition: CH_4	%	56.5	55	65	55	55
CO_2	%	42.5	44.0	34.0	44.0	44.0
Production of CH_4	nm^3 CH_4/day	16 206	6 122	2 867	3 061	4 155
	nm^3CH_4/y	5 915 203	2 234 673	1 046 520	1 117 292	1 516 718
	%	100	37.8	17.7	18.9	25.6
Production of CO_2	nm^3 CO_2/day	12 171	4 898	1 500	2 449	3 324

return rate (IRR). The obtained indicators allow considering the described project quite attractive for investors to be actually realized.

However, given the uncertainty of many factors in biomethane projects, the profitability of biomethane production from intermediate crops can be quite sensitive. The main factors of uncertainty include technical, political, and social ones (Cazier and Cartier, 2024), which, as a result, can jointly affect the project revenue and operational expenditure, and therefore its profitability. For example, the technical factors may include the uncertainty of the biochemical potential of methane from a certain type of raw material during the project life cycle, or the efficiency of bioconversion of raw materials into biogas under the adopted technological scheme of the process, unpredictable production downtime due to technical or other factors, etc.

The political factors may comprise a change in priorities for determining sustainable feedstocks or approaches to the formation of biomethane prices, the introduction of trade restrictions, etc. Social factors could include restrictions on the construction site and scale of biomethane projects due to the population's non-perception of the environmental and sanitary impacts of their operation. Among the factors affecting biomethane projects' profitability, the biomethane and liquified CO_2 sale price are the weightiest, while CAPEX influences to a lesser extent. The estimated OPEX has less uncertainty since it is mostly tied to motor fuels prices, which are interdependent with other energy prices, including natural gas and biomethane. Thus, increasing OPEX due to the rise in diesel price will eventually lead to increasing biomethane sale price and may equalize the project profitability.

The performed IRR sensitivity analysis shows that the biomethane sale price significantly affects the project profitability (Figure 2a), while the sale price of liquefied CO_2 has a lesser influence (Figure 2b). If the sale price of biomethane decreases only by 10% (to 81 EUR/MWh), the discounted payback period will rise to 9.7 years with 15.7% IRR. Sensitivity analysis also shows that in case CAPEX goes up by 20%, DPP will increase to 10.3 years with 14.8% IRR. In fact, this situation may bring the project to the verge of its investment attractiveness.

Thus, it is obvious that the project's feasibility is quite sensitive to changes in key economic parameters. Main options for achieving and maintaining the economic success of such projects can lie in providing a high enough biomethane sale price over a long period and finding profitable markets for liquefied carbon dioxide. Reduction of capital costs can also result in higher economic stability of the project. However, the probability of reaching a significant (by 15–20%) decrease in investments is rather low.

Table 3. Economic indicators of the biomethane project

Indicator	Value
CAPEX, million EUR, including:	14.22
Borrowed funds (60% at 8% per annum)	8.53
Own funds (40%)	5.69
OPEX, million EUR/y (without VAT), including:	1.98
Feedstock	1.21
Operating costs	0.29
Logistics of target products	0.39
Revenue, million EUR/y (without VAT), including:	4.87
Biomethane sale	3.92
Liquefied carbon dioxide sale	0.75
Digestate sale	0.19
Net present value (NPV), million EUR	5.78
Internal return rate (IRR), %	19.9%
Profitability index (PI)	0.41
Simple payback period (SPP), years	5.9
Discounted payback period (DPP), years	7.8

Carbon footprint assessment

One of the important aspects of sustainability is the carbon footprint of biogas/biomethane obtained from intermediate crops. According to RED III, the production of biogas/biomethane for transport must provide at least 65% GHG emission savings as compared to 94 g CO_{2eq}/MJ, the fossil fuel comparator. To meet this requirement, GHG emissions during the life cycle of biogas/biomethane from intermediate crops should not exceed 33 g CO_{2eq}/MJ.

The obtained results for each type of biomass within the feedstock mixture are given in Table 4. As a matter of fact, all feedstocks provide the level of GHG emission reduction required by RED III. At that, individually, pig manure has the best result, maize silage has the worst result, and intermediate crops fall in between. The averaged total emission for biomethane as the final product is negative, reaching –13.0 gCO_{2eq}/MJ.

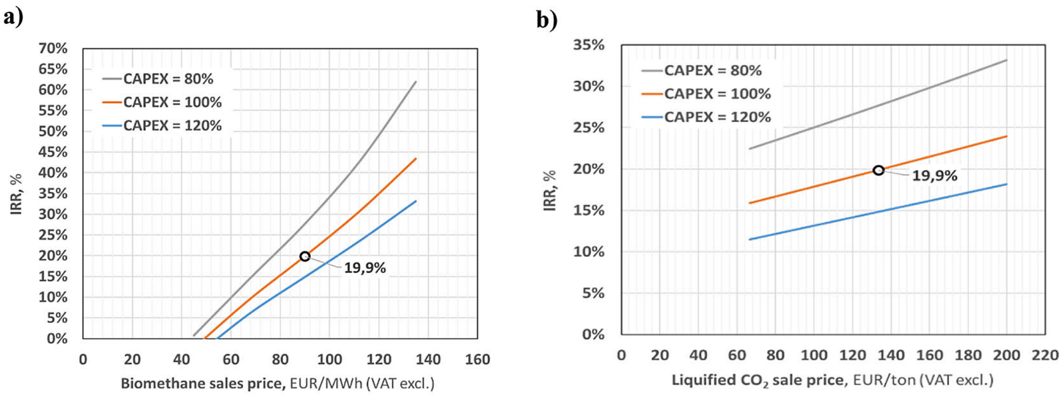

Figure 2. Results of the sensitivity analysis for IRR

Table 4. Total emissions for the final products by feedstock type, g CO_{2eq}/MJ biomethane

Components of emission assessment	Feedstock types			
	Silage of green mass of winter rye	Silage of vetch-oat mixture	Wet pig manure	Maize silage
Emissions from the extraction and cultivation of feedstocks	7.63	10.45	0.00	18.10
Credits for manure	0.00	0.00	-147.50	0.00
Bonus for the case of restored degraded land	0.00	0.00	0.00	0.00
Emissions from processing	17.76	17.76	17.76	17.76
Emissions from the transportation and distribution of the final product	4.60	4.60	4.60	4.60
Emissions from the product usage	0.36	0.36	0.36	0.36
Emission savings from CO_2 capture and replacement	-34.66	-34.66	-34.66	-34.66
Total emission for biomethane as the final product	-4.32	-1.49	-159.44	6.15
Potential for GHG emission reduction for biomethane as the final product, %	104.59%	101.59%	269.62%	93.45%

High potential for reducing GHG emissions in biogas systems based on grass and cover crops is demonstrated in studies for Sweden (Nilsson, 2023; Nilsson et al., 2024). This reduction was assessed as 79–102% compared with diesel fuel, depending on the region where the crops were grown and the time of sowing. These values are close to the results of the present study, where the reduction for intermediate crops is estimated at 102–105%. The study (Rydgård et al., 2025) demonstrates a higher decrease in global warming impact (250 Mg CO_{2eq}) for the case of co-digestion of cover crops, cereal straw, and cattle manure than for mono-digestion of cattle manure and the use of cover crops as organic fertilizer (120 Mg CO_{2eq}). The reduction was assessed for the example of a 1000-ha dairy farm, assuming the replacement of natural gas.

Authors of the study (Launay et al., 2022) point to the positive multiservice of energy cover crops, including climate change mitigation. The extensive usage of cover cops is named as one of the possible ways to reduce the carbon footprint of the energy sector in the study (Słomka and Pawłowska, 2024). The International Energy Agency (IEA Bioenergy, 2022) views cover crop-based biogas and biomethane systems as an important component in the pathway to net-zero emissions and a part of the circular economy in agriculture. All these facts emphasize the necessity of further research and development in this field in Europe as a whole and in Ukraine in particular.

CONCLUSIONS

The economic potential of biomethane from intermediate crops in Ukraine is estimated at nearly 8 Mtoe/y. The results of the carried-out feasibility study show that the respective project can be sufficiently attractive for investors, with a discounted payback period of 7.8 years and a nearly 20% internal return rate. The averaged emissions during the biomethane life cycle might be negative, provided the carbon dioxide released during biogas upgrading is usefully utilised to replace carbon dioxide obtained from fossil fuels. The carbon footprint of biomethane from intermediate crops can reach –13.0 gCO_{2eq}/MJ when a feedstock mixture is used, and about 18% of the total amount of biomethane comes from manure.

REFERENCES

1. Alberici, S., Toop, G., Monchen, B., Peeters, Sh., Peterse, J. (2024). Biogases towards 2040 and beyond. Guidehouse Europe. https://www.europeanbiogas.eu/wp-content/uploads/2024/04/Biogases-towards-2040-and-beyond_FINAL.pdf
2. Belova, I., Shuvar, A., Senyk, I., Sydoruk, B., Yaroshchuk, O. (2024). Application of European approaches for effective utilization of the agro-climatic potential of the region (case of Ternopil region). *Economic analysis, 34*(4), 315–323 (in Ukrainian). https://doi.org/10.35774/econa2024.04.315
3. BIP (2025). Sequential and rotational cropping for biomethane: The potential of sustainable crop rotations across Europe. Biomethane Industrial Partnership (BIP), Task Forse 3.1. https://bip-europe.eu/wp-content/uploads/2025/04/BIP-Task-Force-3.1_Biomethane-Potential-Novel-Cropping-Systems_April2025.pdf
4. Bohushenko, A., Epik, O., Naumenko, D., Łoskot-Strachota, A., Zachmann, G., Zaniewicz, M. (2024). Harvesting green energy: the potential of Ukraine-EU biomethane cooperation. GIZ Project Report. https://greendealukraina.org/assets/images/reports/the-potential-of-ukraine-eu-biomethane-cooperation.pdf
5. Cazier, E.A., Cartier V. (2024). Energy in Europe: The influence of uncertainty on biogas development. *Revue CONFLUENCE: Sciences & Humanités. Incertitudes et prudence. 1*(5), 121–145. https://hal.science/hal-04577853v1/document
6. Dale, B.E., Sibilla, F., Claudio, F., Pezzaglia, M., Pecorino, B., Veggia, E., Baronchelli, A., Gattoni, P., Bozzetto, S. (2016). Biogasdoneright™: An innovative new system is commercialized in Italy. *Biofuel, Bioproducts and Biorefining, 10*(4), 341–345. https://doi.org/10.1002/bbb.1671
7. Dixigroup (2024). Cooperation between Ukraine and the EU in the biomethane sector: prospects and obstacles. Policy brief (in Ukrainian). https://dixigroup.org/wp-content/uploads/2024/03/policy-brief_spivpraczya-ukrayiny-ta-yes-v-biometanovomu-sektori.pdf
8. EBA (2024). Statistical Report 2024. European Biogas Association. https://www.europeanbiogas.eu/wp-content/uploads/2024/12/EBA_stats_report_complete_241204_preview.pdf
9. Geletukha, G., Zheliezna, T., Drahniev, S., Kucheruk, P., Kramar, V. (2025). Advanced biomethane production from intermediate and cover crops. Analytical Note N 1. https://uabio.org/wp-content/uploads/2025/05/Analytical-Note-1-2025-EN.pdf
10. Golz, A-K., Romanov, O., Delidon, R. (2023). Structuring German-Ukrainian cooperation in the biomethane sector. LibMod Policy Paper. https://gas-h2.de/fileadmin/Public/PDF-Download/policy-paper-de-ukr-biomethan-kooperation-libmod-en.pdf
11. IEA Bioenergy (2022). The role of biogas and biomethane in pathway to net zero. Position paper. https://www.ieabioenergy.com/wp-content/uploads/2022/12/2022_12_12-IEA_Bioenergy_position-paper_Final2.pdf
12. IRENA (2022). Bioenergy for the energy transition: Ensuring sustainability and overcoming barriers. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Aug/IRENA_Bioenergy_for_the_transition_2022.pdf
13. Kotsiuba, V. (2023). Designing a carbon neutral energy system of Ukraine: increasing the uptake of biofuels and biomass in Ukraine. UNECE Report. https://unece.org/sites/default/files/2023-06/UNECE_RES_Bio_Report_UA_Final.pdf
14. Launay, C., Houot, S., Frédéric, S., Girault, R., Levavasseur, F., Marsac. S., Constantin, J. (2022). Incorporating energy cover crops for biogas production into agricultural systems: benefits and environmental impacts. A review. *Agronomy for Sustainable Development. 42*, 57. https://doi.org/10.1007/s13593-022-00790-8
15. Levavasseur, F., Kouakou,P. K., Constantin, J., Cresson, R., Ferchaud, F.,Girault, R., Jean-Baptiste, V., Lagrange, H., Marsac,S., Pellerin, S., Houot, S. (2023). Energy cover crops for biogas production increase soil organic carbon stocks: A modeling approach. *GCB Bioenergy, 15*, 224–238. https://doi.org/10.1111/gcbb.13018
16. Magnolo F., Dekker H., Decorte M., Bezzi, G., Rossi, L., Meers, L., Speelman, S. (2021). The Role of Sequential Cropping and Biogasdoneright™ in Enhancing the Sustainability of Agricultural Systems in Europe. *Agronomy, 11*(11), 2102. https://doi.org/10.3390/agronomy11112102
17. Marconi, P., Rosa L. (2023). Role of biomethane to offset natural gas. *Renewable and Sustainable Energy Reviews*, *187*, 113697. https://doi.org/10.1016/j.rser.2023.113697
18. Marsac, S., Quod, C., Leveau, V., Heredia, M., Delaye, N., Labalette, F., Lecomte, V., Bazet, M.,

Sanner, E.A. (2019). Optimisation of French Energy Cover Crop Production in Double Cropping Systems for On-farm Biogas Use. Proceedings of the 27th European Biomass Conference and Exhibition, 27-30 May 2019, Lisbon, Portugal, 40–49. https://doi.org/10.5071/27thEUBCE2019-1AO.4.5

19. Meena, B.L., Fagodiya, R.K., Prajapat, K., Dotaniya, M.L., Kaledhonkar, M.J., Sharma , P.C., Meena, R.S., Mitran, T., Kumar, S. (2018). Legume Green Manuring: An Option for Soil Sustainability, in: Meena, R., Das, A., Yadav, G., Lal, R. (Eds.), Legumes for Soil Health and Sustainable Management. Springer, Singapore, 387-408. https://doi.org/10.1007/978-981-13-0253-4_12
20. Nilsson, J. (2023). Grass and cover crops for biogas production and climate change mitigation: A life cycle perspective. Doctoral thesis. https://doi.org/10.54612/a.hjeem3obq5
21. Nilsson, J., Ernfors, M., Prade, T., Hansson, P-A. (2024). Cover crop cultivation strategies in a Scandinavian context for climate change mitigation and biogas production – Insights from a life cycle perspective. *Science of the Total Environment, 918*, 170629. https://doi.org/10.1016/j.scitotenv.2024.170629
22. Okhota, Y. (2023). Biomethane production in the world and in Ukraine: current status, technology and development prospects. *Economy and Society, 56* (in Ukrainian). https://doi.org/10.32782/2524-0072/2023-56-156
23. Pandey, Sh. (2024). Crop rotation and intercropping techniques, in: Parameswari, P., Prajapat, S., Mohanty, L.K., Kumar, P., Shubhadarshi, S. (Eds.), Modern Concept in Agronomy, 1st ed. ND Global Publication House, Uttar Pradesh, 38–54. https://doi.org/10.5281/zenodo.11051201
24. Selvaggi, R., Valenti, F., Pappalardo, G., Rossi, L., Bozzetto, S., Pecorino, B., Dale, B.E. (2018). Sequential crops for food, energy, and economic development in rural areas: The case of Sicily. *Biofuel, Bioproducts and Biorefining, 12*(1), 22–28. https://doi.org/10.1002/bbb.1844
25. Siddi, M. (2022). Assessing the European Union's REPowerEU plan: Energy transition meets geopolitics. *FIIA Working Paper, 130*, 1–15. https://www.fiia.fi/wp-content/uploads/2022/10/wp130_assessing-the-european-unions-repowereu-plan-1.pdf
26. Słomka, A., Pawłowska, M. (2024). Catch and Cover Crops' Use in the Energy Sector via Conversion into Biogas – Potential Benefits and Disadvantages. *Energies*, *17*(3), 600. https://doi.org/10.3390/en17030600
27. Szerencsits, M., Weinberger, C., Kuderna M., Feichtinger, F., Erhart, E., Maier, S. (2015). Biogas from cover crops and field residues: effects on soil, water, climate and ecological footprint. *International Journal of Environmental and Ecological Engineering, 9*(4), 413–416. https://zenodo.org/records/1126493