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The Potential of Agricultural Biogas Production in Ukraine—Impact on GHG Emissions and Energy Production

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Abstract: Renewable energy production is gaining importance in the context of global climate changes. However, in some countries other aspects increasing the role of renewable energy production are also present. Such a country is Ukraine, which is not self-sufficient in energy supply and whose dependency on poorly diversified import of energy carriers regularly leads to political tensions and has socio-economic implications. Production of agricultural biogas seems to be a way to both slow down climatic changes and increase energy self-sufficiency by replacing or complementing conventional sources of energy. One of the most substantial barriers to agricultural biogas production is the low level of agricultural concentration and significant economies of scale in constructing biogas plants. The aim of the paper was thus to assess the potential of agricultural biogas production in Ukraine, including its impact on energy self-sufficiency, mitigation of greenhouse gas (GHG) emissions and the economic performance of biogas plants. The results show that due to the prevailing fragmentation of farms, most manure cannot be processed in an economically viable way. However, in some regions utilization of technically available manure for agricultural biogas production could cover up to 11% of natural gas or up to 19% of electricity demand. While the theoretical potential for reducing greenhouse gas emissions could reach 5% to 6.14%, the achievable technical potential varies between 2.3% and 2.8% of total emissions. The economic performance of agricultural biogas plants correlates closely with their size and bioenergy generation potential.

Keywords: agricultural biogas; bioenergy; biomethane; GHG emission; economic performance; regional analysis; Ukraine

1. Introduction

Production of agricultural biogas can be analyzed and assessed from three essential perspectives, i.e., the ecological, economic and social. In particular the environmental benefits of agricultural biogas production are often emphasized [1–3]. This is important, since one of the goals of the UN's Sustainable Development Agenda is ensuring access to "affordable, reliable, sustainable and modern energy for all". This poses challenges such as "increasing the share of renewable energy in the global energy mix" and "to promote investments in energy infrastructure and clean energy technologies" [4]. Achieving the goals related to reducing the environmental impact of the energy sector is essential, as energy production and consumption are responsible for 72% of global GHG emissions (World Resources Institute 2017, after C2ES Global Emission [5]). According to the FAO [6], agriculture (crop and livestock activities) is responsible for about 11% of global GHG emissions. Today, striving to replace non-renewable sources with energy from renewable sources is one of the critical challenges faced by most countries in the world [7–9]. Globally only about 18% of total final energy consumption comes from renewables [10]. In the case of Ukraine, this indicator is much lower and amounts to only 4.14%. Meeting the challenge of decarbonization requires the involvement of all sectors of the economy globally, including agriculture. Expectations for this sector concern both an increase of the production of renewable energy as well as lowering consumption of fossil energy and reducing greenhouse gas emissions [6].

Ukrainian greenhouse gas emissions are at 341.5 Mt CO_2e [11], which corresponds to 0.86% of global emissions (and break down into 0.74% of emissions from energy, 0.07% from agriculture, 0.03% from industry and 0.02% from waste) [5]. Due to the economic crisis Ukraine's GHG emissions decreased by 55% from 1990 to 2012. However, the carbon intensity of Ukraine's economy remains almost five times the world average and more than three times higher than European OECD countries [12]. One of the ways to reduce greenhouse gas emissions generated by agriculture is the production of agricultural biogas from organic fertilizers [13,14]. Utilizing organic fertilizers in such a way not only makes it possible to replace a certain amount of energy from fossil fuels with renewable energy, but also reduces methane emissions, which take place at traditional storage sites and in the application of manure and slurry [15–19]. It is assumed that with the reduction of each kilogram of CO_2 that would be emitted in the of burning of fossil fuels, the processing of natural fertilizers into biogas additionally reduces methane emission by the equivalent of 1 kg of CO_2 [20].

The second prerequisite for the production of agricultural biogas are various benefits for farms and the food industry as well as for society [13,20,21]. The production of agricultural biogas can be a way to diversify and improve farm income [20,22,23], to utilize organic biomass from the agri-food industry (fruit residues, residues from the meat and dairy industry, post-slaughter waste, distillery waste) [24] and to manage the excess organic fertilizers produced on farms—especially in countries with intensive livestock production [20,25]—as well as a method of obtaining valuable fertilizers such as struvite [2,25,26]. It should be mentioned that the fertilizing value of the digestate, which apart from the biogas is an outcome of the biogas plant, is at least as good as that of animal manure [27,28].

However, the production of agricultural biogas is not only a way to limit GHG reduction but also increases energy independence and security, both for farms and entire countries [20,29,30]. The search for alternative energy sources to increase energy security is exceptionally substantial for countries that depend on energy imports from other countries. One of these is Ukraine, where for political reasons increasing energy self-sufficiency in the energy supply structure is particularly important [31]. The political tensions between Russia and Ukraine have worsened economic collaboration between the two countries and revealed the dangers of being energy dependent on Russia. Even though Ukraine is not currently importing natural gas from Russia, its dependence on imported fuels (mostly from the EU) is still substantial. At the same time, Ukraine has a large agricultural sector with largely untapped production potential. This creates an opportunity for a significant increase in agricultural production [32] and, consequently, the amount of waste biomass that could be a substrate for feeding agricultural biogas plants. The need to ensure Ukraine's energy independence is one of the strategic goals for upcoming years, emphasized by the government [31]. Despite the fact that in the past decade some studies have attempted to analyze the availability of domestic livestock residues and asses the capacities for biogas generation in Ukraine [33–44], the real potential for biogas production still remains poorly recognized. Especially there is a lack of studies taking the regional dimension into account.

In this context, the study aims to assess the potential production of agricultural biogas from animal manure in Ukraine, its GHG mitigation potential and biogas plants' economic performance in terms of meeting the country's energy demand.

2. Background Information

2.1. Agricultural Biogas as a Renewable Energy Source (RES)

More than half of all greenhouse gas emissions from agricultural production is generated by the livestock sector (enteric fermentation, manure left on pasture, manure management) [45]. The most important GHG emissions from livestock production are enteric fermentation in ruminants, manure left on pastures and manure applied to soils [46]. A tangible share of agriculture in greenhouse gas emissions indicates the need to increase the involvement of agriculture in the processes of emission reductions [47,48]. Biogas is produced in the process of anaerobic fermentation of organic matter, which in agriculture may be provided in the form of farm leftovers and waste. The organic matter can be processed into end products in different ways, but anaerobic digestion is indicated as one of the most effective [49,50]. In practice, the remnants from farms are often supplemented by co-substrates, e.g., various organic materials from the food industry. This can be even considered as advantageous both for the smooth course of microbiological processes taking place in the fermenter, as well as for the environment and the economy, as it provides the possibility for the safe disposal of organic wastes used to produce energy [51]. Some crops (e.g., maize) can also be used as co-substrates in agricultural biogas installations [52], but this is controversial because of competition for agricultural land normally used for food production. As a result, public opposition has led to co-digestion becoming less important in many countries, for example Germany, Belgium and The Netherlands [13,53].

Agricultural biogas can be used in several ways, but most commonly it is processed into electricity and heat in cogeneration (combined heat and power—CHP). Depending on the scale of the biogas plants, the electricity and heat can be used within the household or sent to other recipients. Agricultural biogas can also be conditioned to the parameters of natural gas and injected into the gas network or used to power motor vehicles [13,53,54].

The organization of biogas production in agriculture can be carried out according to two general models, although the exact boundaries of these are somewhat difficult to identify. The first is a large-scale biogas plant supplied with substrates by many farmers, and in the second the capacity is adjusted to the scale of a single farm (micro-scale digesters). For example, large agricultural biogas plants are prevalent in Denmark [13], while a model based on micro-installations is most common in Germany [55]. One of the disadvantages of small biogas plants is the lack of economies of scale that can be achieved in larger businesses [56]. However, micro-scale digesters also have strengths, such as independence from fluctuations in biomass prices, more straightforward and less costly administrative procedures and securing farms' energy self-sufficiency [53,57]. Yet despite the advantages, small-scale production suffers higher costs per energy unit generated. For small agricultural biogas plants this issue is essential, as energy from renewable sources in many cases remains more costly than energy from fossil fuels [58]. Because of the high investment costs involved in starting renewable energy production, new energy generation technologies have been heavily subsidized in their early stages of development [59].

2.2. The Ukrainian Energy Situation and Biogas Production Development

The necessity to ensure national energy independence is one of the critical issues that are continuously stressed by the Ukrainian government [31] as one of the goals for the coming years. The government expectations voiced in the 2017 "Energy Strategy of Ukraine until 2035" [31] also stress maintaining the energy supply at 96 Mtoe in 2035 with a nearly equal share of natural gas of 30.2% (29 Mtoe) compared to current level. The share of energy generated from biomass, biofuels and wastes is to substantially increase—up to 11 Mtoe, or 11.5% of the total expected energy supply. The growth of the total renewable energy generation is planned to gradually increase and reach 8% in 2020, rising to 25% by 2035, reaching 23 Mtoe (or 4.4 times the actual value for 2018).

The strategy [31] stresses that in order to achieve the goals for renewable energy sources it is crucial to increase the use of biomass in the generation of electricity and heat by: (1) stimulating biomass use as a fuel in enterprises that produce biomass as a byproduct, (2) informing about the possibilities of biomass use in individual heating, and (3) supporting the creation of competitive biomass markets. The creation of proper logistics system and infrastructure aimed to collect and transport the biological raw material is necessary to ensure the achievement of these goals.

Despite the government and business efforts, the growth both of total renewable energy generation and the energy from biomass alone, biofuels and wastes are falling behind their expected growth rates defined in the above strategy, which underlines the need to intensify efforts toward structural transformations in energy generation. Biogas generation plants, in this case, are among the crucial drivers of change that can help achieve the targeted transformation values, serving both the country's energy independence and working towards a nationwide switch to renewable energy.

Biogas plants in Ukraine are a relatively new form of energy generation. Even though the first such plant was built in 1993 on a pig farm in the Zaporizka region, until 2012, only four biogas plants were functioning in agricultural enterprises [34,60]. There may be a slight confusion, since in 2013 [61] Ukraine's State Agency on Energy Efficiency and Energy Saving reported the first biogas plant as operating only in that year. However, the reason for this is that the agency monitors only the biogas plants supplying the energy utilizing the feed-in tariff, which was introduced for biogas plants in 2013. Since then, their numbers have been steadily growing, reaching 21 units by the end of 2019 with an overall generation capacity of 59 MWe [62].

Overall, state support for renewable energy generation in Ukraine intensified in 2008 with the introduction of feed-in tariffs [63]. Nevertheless, for several years there has been a visible imbalance in the development of particular types of renewable energy generation plants, as the feed-in tariff was not available to some types of plant. This was the case of the biogas plants, as the only bioenergy generation supported by the feed-in tariff was based on crop biomass. In April 2013 the legislation was changed, and all types of generation plants based on biogas and biomass were covered. Nevertheless, the tariff levels were highly differentiated between the renewable energy types, thus giving most preferences to solar and hydro energy. The rate for solar energy was set at €0.3393 to €0.3586/kWh, hydro energy at €0.116316 to €0.19386/kWh, while the tariff for generation based on biomass and biogas was €0.1239/kWh [64] (pp. 19–24) and was expected to gradually decrease until 2030. It was only in 2017 that the tariff for biomass and biogas was set at a constant €0.1239/kWh with 2030 as the cut off year [65], which created additional security and potential viability for current and future investments. One of the key advantages of the feed-in tariff that it is set in euro, since the value of Ukrainian currency (UAH) has been highly volatile in the past decade. There are also numerous preferences for investors, such as preferential import tariffs for equipment bought for the construction of power plants based on renewable energy technologies [66].

Experts emphasize several issues with the Ukrainian feed-in tariff, all of which are connected with institutional aspects of the Ukrainian economy and legislation [67]: (1) the tariff cannot be applied for mixed energy generation, (2) while each investor needs to know if it will be possible to sell the energy at the feed-in tariff, this is not possible until the investment is fully operational and production is permitted, (3) in order to receive the permit for the feed-in tariff, 50% of the energy generation plant construction/equipment costs need to be of Ukrainian origin.

Due to particular economic and institutional aspects, so far the main investors in Ukrainian biogas generation plants have been the agro holdings [68], with the largest agricultural enterprises being involved in primary agricultural production itself. However, as the construction of biogas plants gains in intensity due to recently fixed feed-in tariff, it is expected that more entities will use this opportunity to expand their potential income.

2.3. Ukrainian Agriculture as a Feedstock Supplier for Biogas Generation

Despite the country's long-term political, financial and economic instability, agriculture in Ukraine is one of the few sectors managing to increase production and steadily expand on foreign markets. The 10% share of the agricultural sector in real Ukrainian GDP and 39% share in total export value reveal one of the current essential specializations of the Ukrainian economy [69].

The good conditions for agriculture in Ukraine have long been known [70], as country's geographic position and its climate and soil quality are elements of a highly beneficial environment both for crop and livestock production. In 1991 (the last year when the share of livestock production exceeded the value of crops) the relationship between the value of the agricultural subsectors (crops to livestock) was 49.4% to 50.6% [71]. Adaptation of the Ukrainian agricultural sector to market conditions and its structural transformation since the beginning of the 1990s have changed these proportions, gradually shifting the focus towards crops and showing a gradually intensifying decline in livestock. As of the 2018 [72] (p. 287) value-wise the proportion between the two subsectors was 73.7% for crops to 26.3% for livestock. The livestock inventory at the end of 2018 [72] (p. 287) included 3.3 million head of cattle (including 1.9 million dairy cows), 6.0 million pigs, 1.3 million sheep and goats, and 211.7 million head of poultry.

Currently, livestock production in Ukraine and its development trend varies greatly depending on the subsectors. Thus, the beef and dairy products are in continuing decline, together with the production of pigs. The poultry subsector stabilized in the early 2000s and since then by 2019 had almost regained its initial level (falling back by only 14.0% compared to the 1991 figures).

Key factors influencing the decline of the livestock sector were the issues with adaptation to the market conditions in the 1990s, a shift the focus of crops from domestic to foreign markets (with the domestic market shrinking from ca. 52 million people in 1991 to almost 42 million by 2019) with a simultaneous decrease in areas under fodder crops (over six-fold, from 12 million ha in 1991 to 1.8 million ha in 2018) leading to a price increase, an overall profitability decrease in livestock production, as well as the inability of farms to comply with the changing requirements regarding production processes, quality and safety of products. Due to these factors, livestock production is either concentrated in medium and large agricultural enterprises (those producing marketable products) or small family farms for self-sustenance (mostly producing non-marketable commodities).

Despite the current difficult situation in the livestock sector, there is a potential for positive change. According to economic forecasts [73] the sector's physical output is to increase by 2030, even though the declining trend in livestock numbers will remain. The driving force is the domestic consumption of meat and dairy products as a result of growing consumer income.

The key messages in Ukrainian scientific publications [74–76] stress the need to support the transformation of the livestock sector. The sector should be reformed towards innovative and cost-effective production technologies and processes, as well as to ensure and diversify its income-generation abilities to maintain its resilience. It is crucial to maintain country's food security [77]; measures aimed to support the development of livestock sector were therefore also included in the 2020 national budget [78]. The search for reserves, including cutting costs and expanding revenues, is one of the ways to improve the economic viability of livestock farms, in which the generation of biogas, as a by-product of their primary economic activity, could aid farms of various sizes and organizational forms in additional income generation. This would also contribute to building the capacity for national energy independence and help to transform the energy sector into more environmentally and climate-friendly renewable technologies.

3. Materials and Methods

The production of agricultural biogas depends mainly on the availability of a suitable substrate. Data on the number of main farm animals (cattle, pigs, poultry) were therefore collected in order to determine the possibility of producing agricultural biogas. The polarized structure of Ukrainian agriculture, resulting in the presence both of large commercial entities and numerous small individual farms, made it necessary to collect data on the number of animals regarding the legal form of the farm, distinguishing commercial farms and small family farms. The basic source of data used in the study was that published by the State Statistics Service of Ukraine (Ukrstat), as well additionally obtained from Ukrstat's detailed unpublished data.

Determining the number of animals made it possible to estimate the quantity of natural fertilizer (animal excrement) available for biogas production. The estimates were based on the research and legislation sources providing amounts of manure obtained per group of animals [79,80]. The theoretical potential of biogas production was established based on the amount of substrate determined [81]. The assumed manure production and biogas yield coefficients are presented in Table 1.

Table 1. Manure production and biogas yield coefficients.

	Cattle	Pigs	Poultry
Manure production (/head/year)	16.8	2.92	0.1
Biogas yield (m^3/t of fresh matter)	25	24	51.3

Source: own elaboration.

The volume of available substrates and potential biogas was determined for regions of Ukraine based on data from agricultural enterprises but excluding small family farms. This is due to the significant fragmentation of family farms, resulting in a very high number of units (4.6 million in 2018 [82], a relatively small number of animals per farm, as well as the limited investment opportunities of these farms, it was decided to omit the theoretical potential of biogas for these farms in further analyses.

The technical potential of agricultural biogas production was determined assuming that it is technically possible to create a biogas plant with a minimum power of the CHP unit exceeding 10 kWe, which if feeding only with slurry and manure requires a stocking level of about 30 livestock units (LU), which is an equivalent of 30 adult cows (for details see: https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Livestock_unit_(LSU)). Based on the Ukrstat data on herd size, the commercial farms were divided into categories regarding potential biogas generation: below a technical threshold, small, medium and large.

In the small farms, with herds from 30 to 100 LU, a micro-biogas installation ensuring an appropriate amount of biogas for a 25 kWe cogeneration unit was analyzed as a representative example. For medium-sized farms, biogas plants with a scale corresponding to the aggregate power of 100 kWe were assumed, with 750 kWe for the largest farms. The number of potential biogas plants required to achieve the technical potential of biogas production on a national scale was determined on the basis of assumptions about the amount of manure available. The structure of farms in terms of the size of animal herds was analyzed at national level. Due to the insufficient number of objects, mostly the largest farms, Ukrstat does not provide complete data on the herds' structure in the regions.

The technical potential of biogas production on farms was calculated on the basis of the amount of manure available that could be used for it. In order to compare the amount of energy produced in biogas plants to the current demand, the amount of methane that could be produced was determined (assuming that biogas contains 55% methane) as was the amount of electricity that could be produced from it. The comparison of the amount of biomethane produced with natural gas consumption can be considered to a limited extent. The existing technologies for purifying biogas to grid parameters are still challenging to obtain for small-scale installations and relatively expensive [83]. The purpose of this comparison is only to determine the possible scale of natural gas substitution by biomethane from a biogas plant.

Comparing the potential electricity generation with existing demand assumes the use of existing technologies. For the calculations, it was assumed that 1 m^3 of biogas has an energy value of 20 MJ [84] and the CHP aggregate efficiency for electricity production is 40% [84,85], which finally gives 2.2 kWh electricity per cubic meter of biogas. Due to transport difficulties and thus low chances of commercial use the heat generated during cogeneration is omitted from the bill.

Under the above assumptions, economic analyses were carried out for the three sizes of biogas plants. The essential technical parameters of the biogas plant considered were determined using the tools provided as a result of the work on the Bio Energy Farm 2 (BEF2) project [86]. The analyses took the operating conditions of biogas plants similar to those in south-east Poland (near the Ukrainian border). For economic analyses, the Ukrainian feed-in tariff for biogas generated electricity (0.1239/kWh—see Section 2.2 for details) was applied. The assumptions regarding the investment costs were based on the results of the BEF2 project and similar studies [87]. A 15-year operation of the installation without general repairs was assumed.

The environmental effects of using the technical potential of biogas production were then assessed. It was assumed that the utilization of a significant part of manure would reduce emissions due to manure management in proportion to the amount of manure used. In addition, it was assumed that the potential use of biogas as a substitute for natural gas would reduce GHG emissions by 1023 kg CO_2e per 1 m^3 [88] while substituting 1 kWh of electricity by electricity generated in biogas plants would reduce CO_2e emissions by 660 g [89]. The profitability of the biogas plants was analyzed, taking into account revenues from electricity sold and the operating and maintenance costs. The substrate cost was not taken into account, as using manure available on-farm was assumed. The economic viability criterion was an internal rate of return of 0% (IRR > 0%), which means that investment outlays will be recovered after 15 years of operation. The fulfilment of such an assumption does not mean that a given investment is attractive from an economic point of view, but only that it does not generate losses.

4. Results

The parameter that directly determines the amount of biogas produced from manure is the number of animals kept. Theoretically, manure from any animals can be converted into biogas. However, taking into account the technical requirements and financial expenditures, only some of the manure can be managed effectively. Due to the dual structure of farms, it can be assumed that in Ukraine only farms listed as enterprises meet conditions to operate a biogas plant. Thus only approximately 1.14 million head of cattle, 3.4 million head of pigs and 118.9 million head of poultry may be the assumed as suppliers of the substrate for the biogas plants (Table 2).

Table 2. Farm animal stocks in Ukraine (2018) in thousand head.

	Cattle		Pigs		Poultry		Sheep and Goats	
	All Farms	of Which Enterprises	All Farms	of Which Enterprises	All Farms	of Which Enterprises	All Farms	of Which Enterprises
Ukraine total	3339.3	1138.2	6024.8	3395.6	211,614.7	118,812.9	1269.9	182.3
Vinnytska	239.4	81.4	251.4	91.4	32,588.6	24,107.1	33	3.5
Volynska	130.3	44.7	285.9	81.8	7560.1	4634.9	16.3	1.2
Dnipropetrovska	122.7	31.9	362.4	280.1	19,521.9	15,325.4	57.6	10.5
Donetska	60.3	27.6	455.7	423.3	5146.7	3181.3	41.6	6.8
Zhytomyrska	189.4	55.4	146.6	40.3	7491.7	583.1	27.5	5.1
Zakarpatska	122.9	1.9	242.7	19.7	3240.7	161.3	153.8	8.4
Zaporizka	91.5	19.3	217.5	145.1	4784.6	2527	63.6	21
Ivano-Frankivska	136.2	12.2	310.7	214.7	4812.7	1772.7	28.1	3.8
Kyivska	117.1	82.9	480.7	394.5	28,389.2	19,913.4	31.2	9.5
Kirovohradska	89.7	25.8	220.5	133.8	4996.7	157.4	36.6	4.3
Luhanska	54.1	16.8	43.1	26.1	996.8	49.6	25.2	2.4
Lvivska	170.9	17.6	417.3	263.2	9114.4	3615.7	31.6	4.6
Mykolayivska	98.5	17.2	83.1	41.2	2554.2	739.1	49.5	9.7
Odeska	154.9	22	173	64.1	3173.5	135.9	319.1	44.1
Poltavska	231.3	142.8	322.2	229.3	5650.3	2692.2	47.6	7.7
Rivnenska	118.6	29.5	243.7	34.1	7332.4	2213.2	15.4	0.5
Sumska	146.3	74.9	114.9	51.3	4892.8	1259.1	38.4	5.1

Table 2. *Cont.*

	Cattle		Pigs		Poultry		Sheep and Goats	
	All Farms	of Which Enterprises	All Farms	of Which Enterprises	All Farms	of Which Enterprises	All Farms	of Which Enterprises
Ternopilska	138.7	30.8	339.3	163.7	5241.8	2043.4	14.4	1.2
Kharkivska	180.8	88.7	194.8	99.1	8021.9	3147.4	71	6.8
Khersonska	96	15.4	111.6	63	5828.9	3557.5	41.6	13.5
Khmelnytska	230.2	67.5	325.9	163.2	7091.6	4519.2	27.3	2.3
Cherkaska	161	117.5	358.8	221.8	26,032.7	21,200.1	28.4	3.2
Chernivetska	81.5	8	141.8	52.1	3531.2	1036.4	43.8	4.6
Chernihivska	177	106.4	181.2	98.7	3619.3	240.5	27.3	2.5

Source: own elaboration based on data from the Ukrstat.

This number of animals can provide about 40.9 million tonnes of manure, which, however, makes less than half of the total amount of manure produced (Table 3). When assessing the substrate resources, it is also worth paying attention to the regional diversification of manure production, which determines the biogas potential. In some regions, the amount of available manure produced in enterprises is meagre (the lowest in Zakarpatska—0.11 million tonnes), while in others it is many times higher (e.g., Cherkaska 4.75 million tonnes; Kyivska 4.54 million tonnes). It is worth noting that in regions where enterprises produce little manure, much more is usually produced on individual farms at the same time.

Table 3. Manure production by Ukrainian regions (million tonnes/year).

	Manure from Enterprises (Million t/year)				Manure from Individual Farm (Million t/year)				Ukraine Total
	Cattle	Pig	Poultry	Total	Cattle	Pig	Poultry	Total	
Ukraine total	19.11	9.92	11.92	40.94	36.96	7.68	9.31	53.94	94.88
Vinnytska	1.37	0.27	2.42	4.05	2.65	0.47	0.85	3.97	8.02
Volynska	0.75	0.24	0.46	1.45	1.44	0.60	0.29	2.33	3.78
Dnipropetrovska	0.54	0.82	1.54	2.89	1.52	0.24	0.42	2.19	5.08
Donetska	0.46	1.24	0.32	2.02	0.55	0.09	0.20	0.84	2.86
Zhytomyrska	0.93	0.12	0.06	1.11	2.25	0.31	0.69	3.25	4.36
Zakarpatska	0.03	0.06	0.02	0.11	2.03	0.65	0.31	2.99	3.10
Zaporizka	0.32	0.42	0.25	1.00	1.21	0.21	0.23	1.65	2.65
Ivano-Frankivska	0.20	0.63	0.18	1.01	2.08	0.28	0.30	2.67	3.68
Kyivska	1.39	1.15	2.00	4.54	0.57	0.25	0.85	1.68	6.22
Kirovohradska	0.43	0.39	0.02	0.84	1.07	0.25	0.49	1.81	2.65
Luhanska	0.28	0.08	0.00	0.36	0.63	0.05	0.10	0.77	1.13
Lvivska	0.30	0.77	0.36	1.43	2.57	0.45	0.55	3.58	5.00
Mykolayivska	0.29	0.12	0.07	0.48	1.37	0.12	0.18	1.67	2.15
Odeska	0.37	0.19	0.01	0.57	2.23	0.32	0.30	2.85	3.42
Poltavska	2.40	0.67	0.27	3.34	1.49	0.27	0.30	2.05	5.39
Rivnenska	0.50	0.10	0.22	0.82	1.50	0.61	0.51	2.62	3.44
Sumska	1.26	0.15	0.13	1.53	1.20	0.19	0.36	1.75	3.28
Ternopilska	0.52	0.48	0.20	1.20	1.81	0.51	0.32	2.65	3.85
Kharkivska	1.49	0.29	0.32	2.09	1.55	0.28	0.49	2.31	4.41
Khersonska	0.26	0.18	0.36	0.80	1.35	0.14	0.23	1.72	2.52
Khmelnytska	1.13	0.48	0.45	2.06	2.73	0.48	0.26	3.46	5.53
Cherkaska	1.97	0.65	2.13	4.75	0.73	0.40	0.48	1.62	6.36
Chernivetska	0.13	0.15	0.10	0.39	1.23	0.26	0.25	1.75	2.14
Chernihivska	1.79	0.29	0.02	2.10	1.19	0.24	0.34	1.77	3.86

Source: own elaboration based on data from the Ukrstat.

The calculations showed that the total potential of agricultural biogas production from manure could be estimated at 2.9 billion m^3. However, only about 1.3 m^3 can be produced from manure produced in enterprises (Table 4). Due to the fragmentation of the sector, most of the potential is thus hardly useable in practice. The very numerous (4.6 million) small farms have a low number of animals (on average 10 tonnes of manure per farm per year), which means that it would be impossible to ensure substrate supply even for a small, 10 kWe micro biogas plant. There are large differences in potential between particular regions. More than 50% of the total potential (enterprises) is located in five regions (Cherkaska, Kyivska, Vinnytska, Dnipropetrovska, Poltavska). The most considerable contribution to the generation of biogas potential from enterprises would be poultry, whose share in biogas production would amount to 46.2% (611.3 million m^3), then cattle (36%—477.8 million m^3) and the least pig production (17.8%). A slightly different contribution to the generation of biogas potential can be observed in the case of individual farms—over 58% (923 million m^3) would be generated by cattle.

Table 4. Theoretical biogas yield in manure-based biogas plant in Ukraine.

	Biogas from Enterprises (Million m^3/year)				Biogas from Individual Farms (Million m^3/year)				Ukraine Total
	Cattle	Pig	Poultry	Total	Cattle	Pig	Poultry	Total	
Ukraine total	477.8	238.0	611.3	1327.1	923.9	184.3	477.5	1585.7	2912.7
Vinnytska	34.2	6.4	124.0	164.6	66.3	11.2	43.6	121.2	285.8
Volynska	18.8	5.7	23.8	48.3	35.9	14.3	15.1	65.3	113.6
Dnipropetrovska	13.4	19.6	78.9	111.9	38.1	5.8	21.6	65.5	177.3
Donetska	11.6	29.7	16.4	57.6	13.7	2.3	10.1	26.1	83.7
Zhytomyrska	23.3	2.8	3.0	29.1	56.2	7.4	35.5	99.2	128.3
Zakarpatska	0.8	1.4	0.8	3.0	50.8	15.6	15.8	82.3	85.3
Zaporizka	8.1	10.2	13.0	31.3	30.3	5.1	11.6	47.0	78.3
Ivano-Frankivska	5.1	15.0	9.1	29.3	52.0	6.7	15.6	74.4	103.7
Kyivska	34.8	27.6	102.5	164.9	14.4	6.0	43.6	64.0	228.9
Kirovohradska	10.8	9.4	0.8	21.0	26.8	6.1	24.9	57.8	78.8
Luhanska	7.1	1.8	0.3	9.1	15.7	1.2	4.9	21.7	30.9
Lvivska	7.4	18.4	18.6	44.4	64.3	10.8	28.3	103.4	147.9
Mykolayivska	7.2	2.9	3.8	13.9	34.1	2.9	9.3	46.4	60.3
Odeska	9.2	4.5	0.7	14.4	55.8	7.6	15.6	79.0	93.5
Poltavska	59.9	16.1	13.9	89.9	37.1	6.5	15.2	58.9	148.7
Rivnenska	12.4	2.4	11.4	26.2	37.4	14.7	26.3	78.4	104.6
Sumska	31.4	3.6	6.5	41.5	30.0	4.5	18.7	53.1	94.6
Ternopilska	12.9	11.5	10.5	34.9	45.3	12.3	16.5	74.1	109.0
Kharkivska	37.2	6.9	16.2	60.4	38.7	6.7	25.1	70.4	130.8
Khersonska	6.5	4.4	18.3	29.2	33.8	3.4	11.7	48.9	78.1
Khmelnytska	28.3	11.4	23.3	63.0	68.3	11.4	13.2	92.9	156.0
Cherkaska	49.3	15.5	109.1	173.9	18.3	9.6	24.9	52.7	226.7
Chernivetska	3.4	3.7	5.3	12.3	30.9	6.3	12.8	50.0	62.3
Chernihivska	44.7	6.9	1.2	52.8	29.6	5.8	17.4	52.8	105.6

Source: own elaboration based on data from the Ukrstat.

As mentioned above, the fragmentation of small-scale individual farms limits the practical possibilities for developing agricultural biogas plants, which can only be considered within the category of agricultural enterprises. However, it should be noted that enterprise farms are not uniform in terms of the scale of livestock production either. Estimates show that there are 1947 enterprises below the assumed minimum threshold of livestock production for biogas plant installation (Table 5), which in total would be able to generate 17.2 million m^3 of biogas, which gives 37.7 GWh of electricity, using an average CHP of 2.4 kWe. Such small installations are not used in practice. Hence the possible use of the potential of the smallest enterprises would require cooperation between them (which, however, would generate a problem with substrate transport between farms).

On the other hand, the potential of farms with a breeding scale allowing for the installation of a CHP unit with a capacity of at least 25 kWe can be assumed as technically and organizationally realistic [90]. There are 2527 such enterprises in Ukraine, of which almost half (1259 units) have a substrate to power a CHP unit with an average power of about 24.8 kW. These enterprises can generate over 113 million m^3 of biogas and 250 GWh of electricity. Almost 40% of these (983 units) are enterprises with a substrate that makes it possible to power a 105.5 kWe aggregate. In total, they would be able to generate nearly 830 GWh of electricity. With an installed capacity of 750 kWe (11.3%, i.e., 285 plants), the largest enterprises, which, however, have the most potential for biogas and electricity production, would have the lowest number of plants. Based on 819.3 million m^3, they could generate over 1802 GWh of electricity, which would correspond to over 62% of the entire potential energy production of agricultural enterprises.

Table 5. Potential number of manure-based biogas plants in Ukrainian agricultural enterprises.

	Number of Plants	Manure Processed (Million tonnes/year)	Biogas Produced (Million m^3/year)	Electricity Produced (GWh/year/plant)	Average CHP Capacity (kWe/plant)
Below threshold	1947	0.7	17.2	37.7	2.4
Small ~25 kWe	1259	4.3	113.6	250.0	24.8
Medium ~100 kWe	983	12.8	377.0	829.4	105.5
Large ~750 kWe	285	23.2	819.3	1802.4	790.5
Total	2527	40.3	1309.9	2881.8	142.6

Source: own elaboration.

On average, the estimated potential of agricultural biogas production from manure would meet 3.17% of Ukraine's total electricity demand for electricity or 2.28% for natural gas (Table 6).

Table 6. Technically possible production of agricultural biogas to energy consumption.

Regions	Natural Gas Consumption	Biomethane Production from Biogas		Electricity Consumption	Potential Production of Electricity from Biogas in CHP	
	(Million m^3)	(Million m^3)	Self-Sufficiency Level	(GWh)	(GWh)	Self-Sufficiency Level
Ukraine total	31,623.75	720.5	2.28%	90,820.37	2881.8	3.17%
Vinnytska	835.01	89.4	10.70%	1856.06	357.5	19.26%
Volynska	469.02	26.2	5.60%	835.96	105.0	12.56%
Dnipropetrovska	3338.04	60.7	1.82%	23,463.50	242.9	1.04%
Donetska	1951.27	31.3	1.60%	8478.55	125.1	1.48%
Zhytomyrska	654.96	15.8	2.41%	1292.91	63.1	4.88%
Zakarpatska	415.82	1.6	0.39%	547.65	6.5	1.19%
Zaporizka	1156.19	17.0	1.47%	8958.31	67.9	0.76%
Ivano-Frankivska	1009.35	15.9	1.58%	2966.03	63.6	2.14%
Kyivska	5111.80	89.5	1.75%	9512.36	358.1	3.77%
Kirovohradska	419.71	11.4	2.72%	2536.74	45.6	1.80%
Luhanska	588.74	5.0	0.84%	1344.43	19.8	1.48%
Lvivska	1671.34	24.1	1.44%	2793.79	96.5	3.45%
Mykolayivska	1030.88	7.6	0.73%	3115.23	30.2	0.97%
Odeska	1713.77	7.8	0.46%	2723.88	31.3	1.15%
Poltavska	2276.36	48.8	2.14%	4046.28	195.1	4.82%
Rivnenska	534.06	14.2	2.66%	2462.57	56.8	2.31%
Sumska	878.14	22.5	2.57%	1312.10	90.1	6.87%
Ternopilska	664.68	19.0	2.85%	502.42	75.8	15.09%
Kharkivska	2679.35	32.8	1.22%	4144.44	131.1	3.16%
Khersonska	393.11	15.8	4.03%	1241.05	63.4	5.11%
Khmelnytska	710.61	34.2	4.81%	1787.71	136.9	7.66%
Cherkaska	2109.15	94.4	4.48%	2000.84	377.7	18.88%
Chernivetska	358.41	6.7	1.87%	2001.77	26.8	1.34%
Chernihivska	653.97	28.7	4.38%	895.83	114.7	12.80%

Source: own research.

Self-sufficiency indicators would, however, be significantly differentiated between the regions of Ukraine, which results both from the level of agricultural development (animal production) and from the energy demand resulting from the degree of industrialization in the region (Figures 1 and 2).

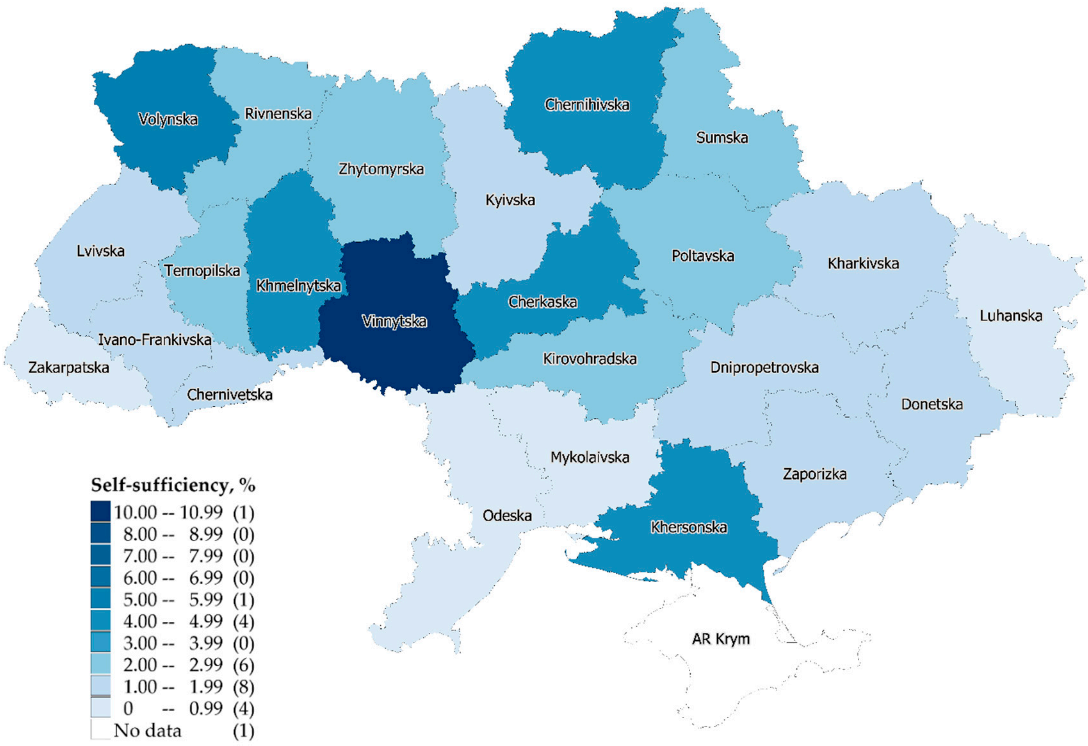

Figure 1. Potential self-sufficiency of biomethane from agricultural biogas plants. Source: own research.

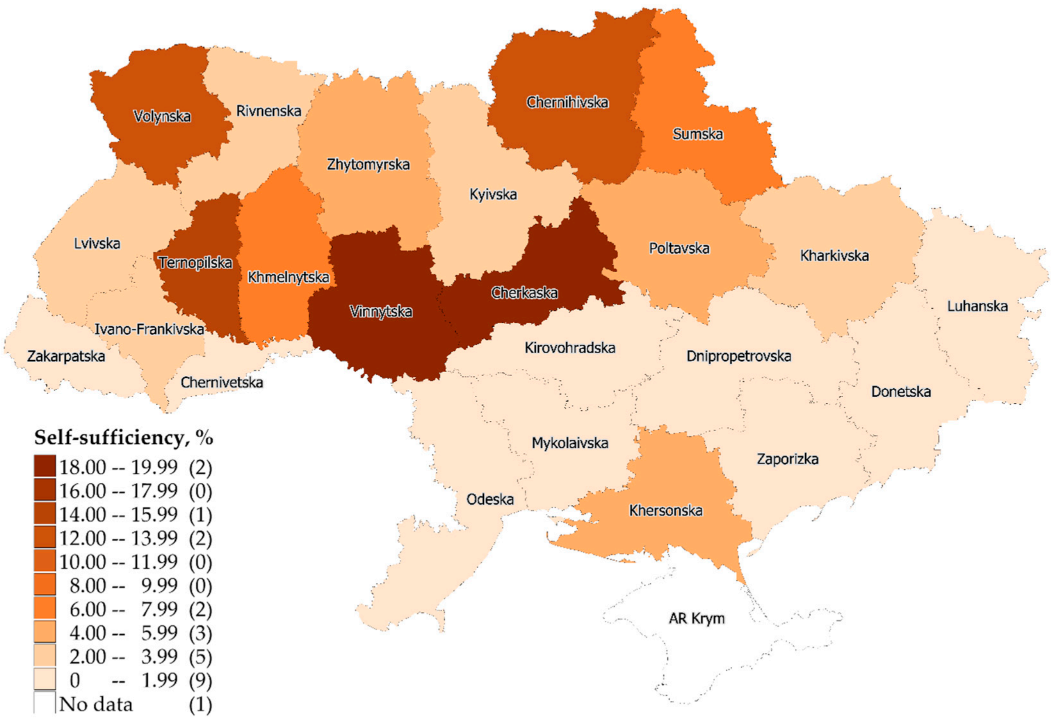

Figure 2. Potential self-sufficiency of electricity form cogeneration in agricultural biogas plants. Source: own research.

The estimated potential agricultural biogas production from manure would not only translate into increasing the energy self-sufficiency (independence) of Ukraine, but also into reducing greenhouse gas emissions. Combined, the level of GHG emissions from Ukrainian agriculture is estimated at 44 kt CO_2e (Table 7), of which 2 kt CO_2e are emissions caused by manure management. The use of the technical production potential would reduce the emissions generated during management by about

0.85 kt, which is 1.9% of GHG emissions from agriculture. In addition, by replacing conventional energy with renewable energy from biogas, emissions could be reduced by around 1.5 kt CO_2e when using biomethane or 1.9 kt CO_2e when using CHP, which would represent 0.65% and 0.84% of Ukraine's GHG emissions due to energy production respectively. The total GHG emission mitigation using the technical potential of biogas production would range from 2.3 kt CO_2e in biomethane production to 2.8 kt CO_2e in electricity production, which would represent 0.68% to 0.81% of the total GHG emission in Ukraine respectively.

Table 7. Impact of agricultural biogas production on GHG emission on Ukraine.

GHG Emissions	Technically Possible	
	kt CO_2e Emissions	**Share**
From agriculture	44	100%
–of which manure management	2	4.5%
–of which avoided due to AD	0.85	1.9%
From energy production	226.3	100%
–avoided due to biomethane	1.5	0.65%
–avoided due to CHP use	1.9	0.84%
Total GHG emissions in Ukraine	341.5	100%
–avoided due to biomethane	2.3	0.68%
–avoided due to CHP use	2.8	0.81%

Source: own research.

As emphasized in the literature review, the practical possibilities of using the potential of biogas (as in other RES) are determined by profitability. Table 8 presents the results of the calculation of profitability and investment efficiency for biogas plants that assume biogas processing in CHP aggregates with a capacity of 25 kWe; 100 kWe, and 750 kWe.

Table 8. Economic feasibility of CHP biogas plants in Ukraine.

Size of Biogas Plant	Small ~25 kWe	Medium ~100 kWe	Large ~750 kWe
Investment cost (EUR/plant)	210,000	600,000	3,750,000
Biogas production (m^3/year/plant)	97,038	360,085	2,728,485
Electricity generated (kWh/year)	164,536	647,365	4,914,943
Operating costs (EUR/year/plant)	8628	25,300	210,750
Revenues (EUR/year/plant)	21,225	83,510	634,027
Simple payback period (years)	16.6	10.3	8.9
IRR	−1.35%	5.1%	7.4%

Source: own research. IRR: Internal Return Rate—The internal rate of return is a metric used in financial analysis to estimate the profitability of potential investments. The internal rate of return is a discount rate that makes the net present value (NPV) of all cash flows equal to zero in a discounted cash-flow analysis.

The estimates show that each of the three investment options generate a positive financial result (the difference between revenues and operating costs). As expected, the result has the lowest value in the smallest enterprises and the highest in the largest ones. For the smallest biogas plant, the simple payback period would be as high as over 16 years. For the largest biogas plant, it would be less than nine years. It should be emphasized, however, that taking into account the change in the currency value over time, under the assumptions adopted, the smallest biogas plant would generate a negative rate of return, which indicates that the investment would not be profitable in this case. It would, however, record the highest rate of return in the largest units. Considering the national scale, building all technically feasible 2572 biogas plants would require investment of nearly €1.92 billion. Those installations would generate a yearly net cash flow of €193 million.

5. Discussion

With a population of 41.9 million and high energy consumption, Ukraine is one of Europe's largest energy markets [26]. Substitution of imported energy has been raised in Ukrainian publications [33] as an important issue to ensure energy independence. Primarily, this concerns the natural gas that could be substituted by domestically generated biogas. Ukraine is a country with high agricultural potential, which also creates great opportunities for using agricultural biomass for biogas generation; however, these opportunities have not been exploited [91]. In particular, this relates to agricultural biogas obtained from manure, which, compared to other RES, does not compete with food for agricultural land and can easily be stored and used on-demand [20,91,92]. In the past decade, Ukrainian scientists have been intensifying their efforts to analyze the availability of domestic livestock residues and substantiate the capacities for biogas generation [33–44] as renewable energy. However, the real potential for biogas remains poorly recognized. It can be assumed that the degree of utilization of this potential is low—the available data indicate the use of 22.3 million m^3 biogas from agricultural waste, which reflects 4.4% of the economically feasible potential [93]. The potential of agricultural biogas production is determined mainly by the amount of agricultural waste available and the possibilities of processing it in biogas plants.

In total, about 3.3 million head of cattle, 6 million head of pigs and 211 million head of poultry are reared in Ukraine. Our estimate indicates that these animals can produce approximately 94.9 million tonnes of manure per year. For comparison, Geletuha et al. [34] indicate 14.4 million tonnes of cattle manure, 5.7 million tonnes of pigs manure and chicken litter, which seems to be an understated value, even assuming significant differences in the assumptions regarding the livestock-keeping system. However, nearly two thirds of the cattle, more than half of the pig holdings and a large amount of poultry are held on small family farms (households), where organizational and financial considerations mean the launch of a biogas plant is unlikely. Our calculations show that the potential of agricultural biogas production (including manure from all farms) can be estimated at 2912.7 million m^3, while the organizational potential covering only manure production from enterprises is 1327.1 million m^3. For comparison, according to the estimates of the State Agency on Energy Efficiency and Energy Saving [93] the potential biogas generation from manure, food residue and sugar waste is approximately 1.6 billion m^3 (about half of which is available for energy production). Other data cited by Yevdokimov et al. [94] suggests that in 2013 the capacity of biogas production from pig farms and poultry farms reached 160 million m^3 and 378 million m^3 respectively. Similar studies in neighboring Poland show that the theoretical potential of biogas from manure (covering all farms) can be estimated at 2762 million m^3 and the organizational potential at less than 800 million m^3 [95].

Taking into account the structure of animal herds in the enterprise farms group, our estimates showed that a total of 2527 plants could operate in Ukraine. In comparison, the Ukrainian State Agency on Energy Efficiency and Energy Saving estimated the potential for biogas plants in agriculture at around 5000 plants with an average installed capacity of 3 MW per plant [96]. However, these estimates refer to the utilization of various categories of agri-food waste (not only manure). Other data from the IEA [97] indicate that organic matter from livestock could support 4000 biogas installations. A comparison of our estimates with others shows quite similar results. However, it should be emphasized that our results indicate the potential plants that could be established in order to develop the existing potential. The use of the organizational potential (manure management with enterprises) would satisfy only 2.28% of the demand for natural gas or 3.2% of electricity demand. The estimates of the Ukrainian State Agency on Energy Efficiency and Energy Saving [96] indicate that utilization of all available agricultural waste (including by-products of the food industry) in 5000 biogas plants could cover 5.7% of Ukraine's electricity consumption. In the context of this value, the result we obtained from manure alone indicates that more than 3% of the country's needs are satisfied and can be considered optimistic.

The analyses revealed that the estimated potential differs significantly between the individual regions in Ukraine, which is a consequence of differences in the structure and scale of animal production.

It is also understandable that the energy-generation potential varies greatly depending on the local peculiarities: landscape and climatic predispositions to either crop or livestock farming (and their particular types), availability of technical, economic and financial potential. For these reasons, the large agro-holdings have concentrated land and allocated their production capacities in the regions with the most beneficial conditions for their activities. As is known, siting of biogas generation plants is most efficient near or even on a local livestock farm (as bioenergy inputs are not transportable over long distances).

Most research, however, does not approach the issue of biogas potential from the regional perspective, especially for all the Ukrainian regions (with one of the exceptions being Kudria [98]). Our analyses indicate that the highest degree of self-sufficiency in meeting energy needs would be observed in central and western Ukraine. In some regions, the biogas produced would make it possible to cover nearly 11% of natural gas consumption or almost 20% of electricity (Vinnytska region). One of the studies [42] on regional capacities for renewable energy generation states that, based on its biomass energy potential (including biogas, biodiesel and bioethanol), the western region of Ukraine (combining Volynska, Zakarpatska, Ivano-Frankivska, Lvivska, Rivnenska, Ternopilska, Chernivetska) could fully cover its natural gas needs. Other research [44] focusing solely on the Lvivska region specified that only biogas plants based on agricultural residues (both crop and livestock) could generate enough to replace 163 million m^3 of natural gas, or 22.9% of its regional consumption as of 2016. Our estimates prove the substantial capacity for biogas generation in the particular regions, yet need to mention the differences in values which come from different methodical approaches: both Bashynska [42] and Yankovska [44] based their evaluations on both the crop and livestock production values.

As mentioned in the introduction, one of the fundamental prerequisites for biogas production (as well as the use of other alternative energy sources) is seeking environmental benefits. The production of biogas, including agricultural biogas, is indicated as an important way to reduce GHG emissions [20,99,100]. According to the World Biogas Association calculations, "biogas and biomethane industries have the potential to reduce global GHG emissions by 10–13%" [101]. The analyses show that, as a result of using the potential, the total level of greenhouse gas emissions would decrease by 5% to 6.14%. In comparison, for the technical potential, it would be 2.3% to 2.8%. The scope for reduction results both from the reduction of emissions due to management and the replacement of conventional energy by renewable energy. The influence of the second factor is particularly important in countries where the energy mix is dominated by high-emission sources such as coal (a situation that also partially applies to Ukraine). However, it is worth bearing in mind that the environmental impacts of biogas generation from manure also depend on many other factors, such as substrate, technology and operating practices [100].

The economic dimension is the third key aspect of biogas production. The economic viability assessment of investments in biogas plants in Ukraine presented in the literature provides similar outcomes. In 2017 Shanda Consult [96] published report which concludes that "small" (<300 kWe) biogas plants are not economically attractive. Slightly bigger plants could be justified only if using heat for one's own purposes, while a chance of fast payback in four to five years is possible for units larger than 1 MWe. This observation is related to the phenomenon of economies of scale, reflecting the degression of unit costs as the scale of production increases. Our analyses show that the IRR of medium (100 kWe) and large (750 kWe) plants analyzed are positive, although close to the average inflation rate in Ukraine. It might thus be concluded that, even if neither investment generated losses in a 15-year period, they would be one of the last priorities on farmers' investment "wish list". Generally, our results confirm Shanda Consult outcome on the economic viability of biogas plants. However, we assumed that plants which do not generate losses are economically viable, while the [96] experts set higher requirements to consider the investment economically attractive.

Financial support is a decisive factor for the profitability of many renewable energy sources, especially in the early stages of development [8,59,93,102,103]. There are many different support mechanisms [104] in Ukraine, one of the key being the subsidized feed-in tariffs.

6. Conclusions

The analyses indicate that in absolute terms Ukraine has a significant potential for the production of agricultural biogas from animal manure, reaching nearly 3 billion m^3. However, the practical possibilities of using this potential are severely limited by the dual structure of agriculture. More than half of the available manure is produced on small livestock farms that are too small-scale to consider investing in biogas plants. Our analyses show that under the current conditions, only biogas plants with a CHP aggregate capacity of around 100 kW could provide a positive return on investment. In practice, therefore, the economically justified production of agricultural biogas can only be carried out by agricultural enterprises, which allows for the satisfaction of over 3% of the country's electricity demand. However, policymakers might consider the possibility of creating programs to support cooperation between small farmers to create collective biogas initiatives (e.g., biogas cooperatives). Increasing the real possibilities of using the agricultural potential in the production of biogas is important both for increasing energy self-sufficiency and reducing GHG emissions from agriculture. The production of biogas from manure will not completely solve these problems, however, as shown by the analyses; in some regions of Ukraine it may make a noticeable contribution to meeting energy needs and reducing GHG emissions from the agricultural sector. In the context of global efforts to replace non-renewable energy sources with renewable sources and increase climate neutrality, the increased importance of agricultural biogas in the energy mix should be one of the goals of state energy policy. However, the potential growth of the agricultural biogas production in electricity generation in Ukraine requires growing interest in this issue from agricultural producers themselves. It is necessary to make them aware that converting manure into biogas can bring economic benefits for farmers and also environmental and social benefits for society as a whole. However, the development of agricultural biogas production also requires further in-depth scientific analyses that would enable the adjustment of academic knowledge from other countries to Ukrainian conditions.

It should be noted, however, that when interpreting this paper's results, one should remember that these are only estimates based on the available statistical data. The substantial obstacle to more precise estimates was the lack of detailed accessible data regarding the particular elements of agricultural activity in Ukraine, including detailed data on the livestock population (divided by the type, age, weight), production technologies (extensive, intensive) and breeding systems. While the agricultural enterprises report their operational data to the Ukrstat, there is still a substantial gap in the data about individual (household) farms, which were not well captured in the analysis. However, having regard to the available literature, the work presented substantially fills the knowledge gap about the problem discussed, and the research results may be the basis for further investigations based on more detailed data when available.

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