energies

Article

The Impact of Manure Use for Energy Purposes on the Economic Balance of a Dairy Farm

Jakub Mazurkiewicz

Ecotechnologies Laboratory, Department of Biosystems Engineering, Poznań University of Life Sciences, Wojska Polskiego 50, 60-627 Poznań, Poland; jakub.mazurkiewicz@up.poznan.pl; Tel.: +48-618487161

Abstract: The use of methane fermentation in mesophilic conditions for the energy use of cow manure and additional co-substrates from the farm can bring a small dairy farm (140 dairy cows) financial benefits of up to EUR 114,159 per year. Taking into account the need to pay for emissions calculated as carbon dioxide equivalent, this profit could be reduced to EUR 81,323 per year. With the traditional direct use of manure, this profit would drop by as much as 60% to the level of EUR 33,944 per year. Therefore, the introduction of fees for emissions may significantly burden current dairy farms. As has already been shown, just compacting and covering the manure (which costs approx. EUR 2000 per year for 140 cows) would give almost twice as much profit—EUR 64,509 per year. Although an investment in a small biogas plant with a cogeneration unit on a family dairy farm may have a payback period of less than 6.5 years and a return of capital employed of 16%, most small farms in the world will not be able to afford its construction without external subsidies. At the same time, it would make it possible to reduce emissions by almost 270 times—from 41,460 to 154 tons of CO_2eq per year—and the possibility of preserving valuable nutrients and minerals and supporting soil properties in the digestate. Therefore, it seems necessary for Europe to introduce a support system for small- and medium-sized farms with this type of investment in the near future in a much larger form than it has been so far.

Keywords: cow manure; compacted and covered manure; fertilizer; biogas plant; fermentation; digestate; GHG; energetic and economic calculation; milk cows; cattle; dairy farm

check for updates

Citation: Mazurkiewicz, J. The Impact of Manure Use for Energy Purposes on the Economic Balance of a Dairy Farm. *Energies* **2023**, *16*, 6735. https://doi.org/10.3390/en16186735

Academic Editor: Eglė Sendžikienė

Received: 26 August 2023
Revised: 16 September 2023
Accepted: 18 September 2023
Published: 21 September 2023

1. Introduction

Most organic waste can be used effectively equally as a collection of high added-value bio-fertilizers, bio-chemicals and material building blocks after biomass processing, and also as an energy carrier—a fuel [1–3]. The latter option is recently considered one of the best organic waste treatment technologies to recover both valuable fertilizing substances and energy from organic waste [4–7], especially with regard to agricultural waste, the biogas produced from them, and, less often, liquid biofuels. These constitute a new approach that should be considered in the context of sustainable development [4,8]. Biogas production is highly beneficial compared to other renewable energy sources and changes the perception of this technology not only in the financial context, but also in the ecological and social context [9].

Currently, the increase in the amount of waste of animal origin is an important problem causing serious environmental problems if not properly treated [10–12]. Biogas from agricultural waste is a renewable energy source that can be used in many applications. Among other applications, biogas can be easily burned in an internal combustion engine in a cogeneration unit, producing electricity and heat [13].

The biogas itself contains 50–75% methane (CH_4) and 25–45% carbon dioxide (CO_2), as well as trace amounts of other gases (hydrogen sulfide (H_2S), nitrogen (N), oxygen (O), hydrogen (H)) [14–16]. Its production is not associated with the formation of most harmful gases, i.e., nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), etc. [4,17].

On the one hand, agricultural waste can be an easily accessible and cheap source of renewable energy; on the other hand, the improper use of these streams is considered one of the main sources of methane and nitrous oxide atmospheric release—two gases with a high warming potential. In the agricultural sector, emissions related to animal production account for approx. 14.5% to 16.5% all of emissions caused by human activities [18–20], and produce (compared to global emissions) accounts for about 37% and 65% of all methane and nitrous oxide release [21–24]. Dairy production accounts for about 20–30% of this value.

The above values are often quoted, although there is no shortage of assumptions that emissions from livestock cover a much wider range. The United Nations Food and Agriculture team recently reported a much lower figure, which puts farm animal emissions at 11.1% of total greenhouse gas (GHG) emissions [25–27]. In turn, other scientific sources say that the production of GHG in this case may be as much as 19.6% [27,28].

According to the literature sources, 70% to 90% of greenhouse gases released come from the farm itself (excluding transport, feed, etc.) [29–31]. Such a large percentage is therefore caused by activities inside the farm—i.e., the mitigation potential of pollution is very large [10].

The largest GHG streams from dairy farm production are ammonia and nitrous oxide emissions from enteric fermentation, manure storage and handling, and agricultural crops and pastures growth activity [32–35]. Among the sources of GHG, one could also mention the emissions of carbon dioxide equivalent (CO_2eq) from the combustion of fossil fuels and the decomposition of lime used on farmland and pastures, but these sources are very diffuse and difficult to avoid. In the case of potentially generated nitrous oxide (N_2O), a distinction should be made between direct emissions from the farm and emissions from ammonia and nitrates leaving the farm, which may eventually be converted to N_2O in other ecosystems. Although they are often treated as independent sources, there are interactions that affect the overall emissions [32,33,36].

In the case of slurry, there are many solutions to mitigate GHG emissions, including the use of chemicals or special technical solutions [37]. For farmyard manure there are not so many ways to reduce emissions, but there is one that farmers know well and that seems to be relatively cheap and simple. This solution is to compact and cover the manure during storage [37–39]. This procedure is crucial to significantly reduce the decrease in GHG and ammonia emissions and the decrease in the value of the manure itself (loss of carbon, nitrogen, potassium, etc.).

The decomposition of manure depends on how it is stored, including placement. In a loosely stacked pile, after some time, the temperature may reach over 60 °C and the decomposition process will be very intensive [40,41]. However, this situation ultimately results in significant losses of organic matter. To prevent this, manure should be stored in well compacted heaps, where the temperature is between 30 and 40 °C. Manure contains simple sugars, starch, pectins, cellulose, hemicellulose and lignin. During the decomposition processes that occur under proper storage conditions, these compounds are transformed into simpler organic compounds and, depending on the availability of oxygen, to carbon dioxide and water (in aerobic conditions) and carbon dioxide and methane (in anaerobic conditions) [39]. With regard to nitrogen, in manure it is present in the form of mineral and organic nitrogen—the latter as proteins. In the process of decomposition, proteins are converted into amino acids and then into ammonia, which is released directly into the atmosphere. Factors that reduce nitrogen losses include the binding of ammonia by the forming organic acids, as well as its binding and processing into protein compounds by microorganisms. For this to happen, there must be conditions suitable for the development of microorganisms, including the right amount of easily degradable carbohydrates [42–44]. In the upper part of the heap, ammonium nitrogen under aerobic conditions is converted to nitrate nitrogen, while in the lower part of the manure it is converted to molecular nitrogen and nitrogen oxides [45]. Mineral nitrogen contained in manure, in the form of ammonium and nitrate, can be immobilized and will be released only during the application of manure to the soil. Phosphorus in manure is present in mineral and organic compounds, which undergo significant mineralization during storage. As a result, orthophosphoric acid is formed, which combines with cations to form salts. As a result, this element becomes available to plants. In addition, the formed compounds are characterized by poor movement to deeper layers of manure, which does not lead to their leaching, although there are studies that indicate that under favorable conditions there may be a loss of up to 25% as a result of leaching [46]. Manure also contains calcium and magnesium in the form of various mineral and organic compounds. In the mineralization process, these compounds are transformed into easily soluble forms, but their migration to deeper layers of manure, and thus the risk of significant leaching, is relatively small [47]. The situation is different with potassium, which is usually present in manure in the form of a cation, which significantly contributes to its leaching. Potassium losses from manure are estimated to be up to several dozen percent. Ultimately, the fertilizing and energy value of manure, as well as the emissivity, depends primarily on the chemical composition of this natural fertilizer—that is, mainly on the feed and the method of storage. For estimation purposes, when calculating potential emissions from manure, in the case of methane, the determination of the share of volatile matter is often used [48], while for nitrous oxide emissions, it is most convenient to determine the abundance of nitrogen compounds [49,50]. In the use of manure as a substrate or co-substrate in anaerobic digestion processes, the more biogas produced the higher the content of organic matter.

The problem of emissions from cow breeding, mainly dairy cows, is significant—as much as 70% of all manure produced on farms in Europe comes from only six European countries, including Germany, Spain, Italy, France, Poland and the United Kingdom, and it is worth noting that as much as 75% of all manure is cow manure [51,52], of which over 70% (some sources say 90%) is used to fertilize the land, albeit in an inefficient way [53–55].

Proper management of cow manure is a challenge facing most of the world. However, this article focuses on manure from so-called "deep bedding"—a practice which is characteristic of several countries in western Europe and most of eastern and central Europe [10,41,55,56].

When manure is misused, nutrients can be a major source of soil, water and air pollution, and can have negative impacts on biodiversity and climate. That is why, as part of the Farm to Fork strategy (one of the main pillars of the European Green Deal), the European Commission aims to reduce nutrient losses by at least 50% by 2030, while ensuring that soil fertility is not impaired and, at the same time, farmers obtain a stable and fair income, taking into account the full range of goods they provide [57]. One of the aspects of the strategy will be to support the production of renewable energy from agriculture, enabling farmers to invest in biogas and biomethane for their own needs [58]. As shown in a large number of sources, methane fermentation is the main technology that enables an economic and ecological reduction in the negative effects of manure management, while further enabling agricultural use of waste, such as digestate as a valuable fertilizer [49,59–61]. Methane fermentation, and above all the need for a very short storage period, allows for the reduction in greenhouse gas emissions related to manure management by several dozen percent [20,49,62]. In addition, the possibility of producing ecological fuel that can replace conventional sources of heat and electricity [59,63–65] increases farm income [65–69]. Recently, there have been more and more statements that it is at the farm level, and not at further stages of the production chain, that ecological (and indirectly also economic) costs should be calculated [70–74].

Based on the results of several projects [75–77] and on ongoing research under the DairyMix project [78], it is puzzling, however, why still only a few farmers have decided to properly store manure (compressing and covering) or use it for energy purposes by adopting a solution such as a establishing a biogas plant equipped with an aggregate for the production of electricity and heat (combined heat and power—CHP). An innovative element in this work is the indication of how much improper manure management affects the energy and economic losses of typical dairy farms, taking into account mainly (apart from the loss of nutrients, minerals and caries) the losses related to GHG emissions during manure storage. The influence of the manure storage method—the standard being in a heap without and with cover and compaction—on farm income in comparison with ongoing manure fermentation with the use of other by-products (substrate materials) from a dairy and agricultural farm was also assessed. Although laboratory and field studies have been carried out in many countries on the storage and use of manure for energy purposes (biogas), sometimes also in combination with GHG emissions [12,22,37,40,45,56,79,80], they lack a comprehensive analysis, including the impact of emissions on the economic balance of the farm and the costs associated with compacting and covering the manure.

2. Materials and Methods

The basis for the analyses was mainly the method of cow manure management, assuming that it is used as a:

- natural fertilizer (collected on an open and uncompacted heap and with a cover and compaction), or
- manure (collected daily as a biogas plant substrate and its subsequent use as fertilizer (digestate) after undergoing methane fermentation processes.

The estimates presented in this work are divided into main stages: an analysis of the current activity of a cattle breeding farm with agricultural production (milk production and feed production) and using a biogas plant with a cogeneration unit (producing heat and electricity).

As part of the second stage, a simplified economic and energy balance was presented for two variants using co-substrate manure in fermentation processes with agricultural waste/by-products without and with taking into account the avoided emissions of carbon dioxide equivalent.

The presented economic and energy balances include the following variants:

- milk + fertilizer, M + F,
- milk + fertilizer + protection (compacted and covered), M + F + P,
- milk + biogas and CHP, M + B,
- mentioned above + emission allowances (costs related to the need to pay for CO_2eq emissions), "x"* + EA (*x − the appropriate symbol for the variant).

2.1. Materials and Methodology of the Research

The study used data from in-situ research on a farm near Głogów (northern Silesia) that incorporates dairy cattle breeding (140 milk cows, including 100 Holstein Friesian and 40 Mixed) in free-stall barns (Figure 1) and 325 ha of agricultural crops. The method was an in-depth interview and analysis of financial and organizational documents as well as recognition of the surrounding market in accordance with the recommendations of the DairyMix project [78].

One of the research methods regarding the costs of compacting and covering manure, due to the lack of sufficient literature data, was obtained as a result of in-depth interviews. Interviews were conducted with 11 farmers during face-to-face meetings on the farm (6 interviews) and by telephone (5 interviews). During in-person meetings, bills for individual cost components were checked and compared with data from 5 farmers interviewed by telephone.

Prices of materials, services and substrates used on the farm were current and came from the last month before the preparation of the article (July 2023).

The basic milk analysis was carried out by the local agricultural station, and the manure analysis at the alma mater in the Ecotechnology laboratory. Manure samples were collected from two places—from a heap lying in the field (Figure 2) and a manure plate located on the farm, 30 m from the cowshed (daily collection, Figure 3).

Figure 1. Free-stall barn on the case study dairy farm (lying place).

Figure 2. Uncovered and uncompacted heap in the field.

Figure 3. Manure on a manure plate at the cowshed.

On the downloaded material, the so-called biogas tests (course and volume of biogas emissions) and related procedures and indicators were applied in order to estimate the emissions of nitrous oxide and methane in accordance with IPCC reports [81–83]. Finally, the study presents comparisons of economic and energy flows for individual stages and variants, together with the determination of the amount of CH_4 and N_2O emissions in CO_2 equivalent units.

The limitations of my research can be stated as follows: dairy farms with the number of dairy cows ranging from 20 to 160; agricultural production 10–400 ha; use of a biogas installation with an electrical power of 4–499 kW; conditions for methane fermentation—mesophilic, liquid technology, substrate feeding 1–3 times a day.

2.2. Calculation of Methane and Nitrous Oxide Emissions

The individual values of the indicators and the method of calculating the final emissions for CH_4 and N_2O were adopted or calculated based on the Tier 2 methodology recommended in the IPCC reports [81–83] using regional data [84].

The emission factor (EF) was calculated according to the simplified Equation (1):

$$EF = V_s \cdot B \cdot 0.67 \cdot 365 \cdot MCF \text{ [kg } CH_4\text{/animal/year]} \quad (1)$$

where:

EF—emission factor,
V_S—volatile excreted solids—4.88 kg/animal/day,
B—production of CH_4 from animal manure—0.24 m^3 CH_4/kg V_S,
0.67—conversion factor,
365—days in the calculation period,
MCF—methane conversion factor to the manure management system.

In accordance with the European procedure contained in international IPCC reports, individual indicators have been adopted as constants for a given region. The MCF value was assumed only at two different levels: 17%, assuming that the manure was stored without compaction and cover, or, if compacted and covered, 3%, and 0% if it was transported to the biogas plant every day. Therefore, the emission factor per cow per year (kg CH_4) was: 48.49, 8.59 and 0, respectively.

The following Equation (2) was used to estimate direct N_2O emissions (N_2O D):

$$N_{2OD(mm)} = N_{EX} \cdot 44/28 \cdot EF_3 \text{ [kg } N_2O\text{/animal/year]} \quad (2)$$

where:

$N_{2OD(mm)}$—direct N_2O emissions,
N_{EX}—N excretion of livestock—114.60 kg N_2/animal/year,
EF_3—emission factor for direct N_2O,
44/28—conversion factor of (N_2O-N) (mm) emissions to N_2O (mm) emissions.

The EF3 index (in kg N_2O-N/kg N) was adopted for deep bedding, covered and compacted and transferred daily to the biogas plant as: 0.01, 0.005 and 0, respectively.

Indirect N_2O ($N_2O_{G(mm)}$) emissions from N volatilization as NH_3 and NO_x were calculated according to the simplified Equation (3):

$$N_2O_{G(mm)} = \text{Nvolatilization-MMS} \cdot 44/28 \cdot EF_4 \text{ [kg } N_2O\text{/year]} \quad (3)$$

where:

$N_2O_{G(mm)}$—indirect N_2O emissions due to volatilization of N,
Nvolatilization-MMS—nitrogen that is lost due to volatilization of NH_3 and NO_x,
EF_4—emission factor for N_2O emissions from atmospheric deposition of nitrogen on soils and water surfaces,
44/28—conversion factor of (N_2O-N) (mm) emissions to N_2O (mm) emissions.

Before substituting the ratios into Equation (3), it is necessary to determine the N volatilization-MMS according to the simplified Equation (4):

$$\text{Nvolatilization-MMS} = N_{EX} \cdot F_{racGasMS} \text{ [kg N/year]} \quad (4)$$

where:

N_{EX}—N excretion per head of livestock,
$F_{racGasMS}$—percent of managed manure nitrogen that volatilizes as NH_3 and NO_x,

$F_{racGasMS}$ (%) was determined per national reports according to the characteristics of the manure management and storage system [64,75–78,81–85]. Sequentially, for faeces: without any mitigation measures, covered and compacted and directed to biogas plants (in %): 40, 20, 10, respectively. Similar indicators were determined for EF_4 (kg N_2O-N/kg (NH_3-N + NO_x-N) volatilized) and were, respectively: 0.05, 0.01, 0.002.

Nitrogen leached into the soil and/or running off during rain (N_2O $_{L(mm)}$) forms another indirect stream of N_2O from manure. Emissions of this type of N_2O according to the simplified Equation (5) are:

$$N_2O_{L(mm)} = \text{Nleaching-MMS} \cdot 44/28 \cdot EF_5 \text{ [kg } N_2O\text{/year]} \quad (5)$$

where:

$N_2O_{L(mm)}$—indirect N_2O emissions due to leaching and runoff,
Nleaching-MMS—amount of manure nitrogen that is lost due to leaching of NH_3 and NO_x,
EF_5—emission factor for N_2O emissions from nitrogen leaching and runoff N leached and runoff,
44/28—conversion factor of (N_2O-N) (mm) emissions to N_2O (mm) emissions.

Before substituting the ratios into Equation (5), it is necessary to determine the Nleaching-MMS according to the simplified Equation (6):

$$N_{leaching\text{-}MMS} = N_{EX} \cdot F_{racleachingMS} \quad (6)$$

where:

N_{EX}—N excretion per head of livestock (on average annually),

$F_{racleachingMS}$—percent of managed manure nitrogen losses due to runoff and leaching during storage of manure,

$F_{racleachingMS}$ (%) was determined in accordance with national reports and experience according to the characteristics of the manure management and storage system [64,75–78,81–85]. Sequentially, for faeces: without any mitigation measures, covered and compacted and directed to biogas plants (in %): 10, 1, 1, respectively. Similar indicators were determined for EF_5 (kg N_2O-N/(kg N leaching/runoff)) and were, respectively: 0.0025, 0.0075, 0.0005.

2.3. Calculation of Carbon Dioxide Equivalent and Fees for the Allowances for Emission

When determining the strength of the impact of individual greenhouse gases on the climate, a comparative conversion factor was used, i.e., carbon dioxide equivalent (CO_2eq), according to which a multiplier of 25 was adopted for methane (range: 25–28 [84,86–88]) and for nitrous oxide 298 (range: 265–298 [49,84,86,87]).

The data presented in this paper are based on information provided under the "Trading Economics Carbon Emissions Allowances Prices" from the European Emissions Trading System (EU ETS), the world's largest market for GHG emission allowances and trading [89]. The operation of this undertaking is as follows—allowances for carbon dioxide (CO_2eq) emissions are first allocated on the basis of EU directives relating to maximum GHG emissions, and only then are they made available in auctions.

According to the EU ETS, EU CO_2eq allowance prices fell to €87 a ton, a two-month low, as investors expect lower demand for allowances due to a weak manufacturing sector [89]. This comes as Germany, one of Europe's largest economies (this year, the largest amount of carbon allowances auctioned or sold took place in Germany [90]), saw a 1.5% fall in industrial production in July from the previous month, beating market estimates for a milder decline and highlighting the impact of higher interest rates on the European industry after a string of worrying PMI data. In April, the European Parliament adopted climate measures to reduce EU greenhouse gas emissions by 62% by 2030, compared to 2005 [89]. The price of allowances on the European Union's carbon market rose above EUR 105 per ton, for the first time, earlier this year, reflecting the increasing costs that factories, power plants and other industries have to bear in connection with the emission of pollutants. Here, the current price of allowances is EUR 92.36 per ton [89].

2.4. Methodology of Biogas Efficiency

The collected samples were tested in the laboratory of Ecotechnology of the University of Life Sciences in Poznań [91]. This unit guarantees a high quality of results and has obtained quality certification of methane fermentation tests granted by the international biogas institution—VDLUFA and KTBL [92,93]. Therefore, the methods of biogas efficiency analysis are based on procedures in accordance with the following standards: VDI 4630 and DIN 38414/S8 [94,95]. A broader description can be found in similar studies [10,41,96].

Research on the biogas efficiency of the so-called batch culture was carried out on a specially constructed stand (Figure 4). It consists of a set of tubes (1) for measuring the volume of the produced gases, in which the volume is read several times a day using the scale (2) and the gas composition is analyzed with a portable analyzer by withdrawing all the collected gas (for averaging) through the upper valve (3). The methane fermentation process itself in mesophilic conditions takes place in a set of glass containers immersed in a water bath and connected with wires to a set of measuring tubes (4).

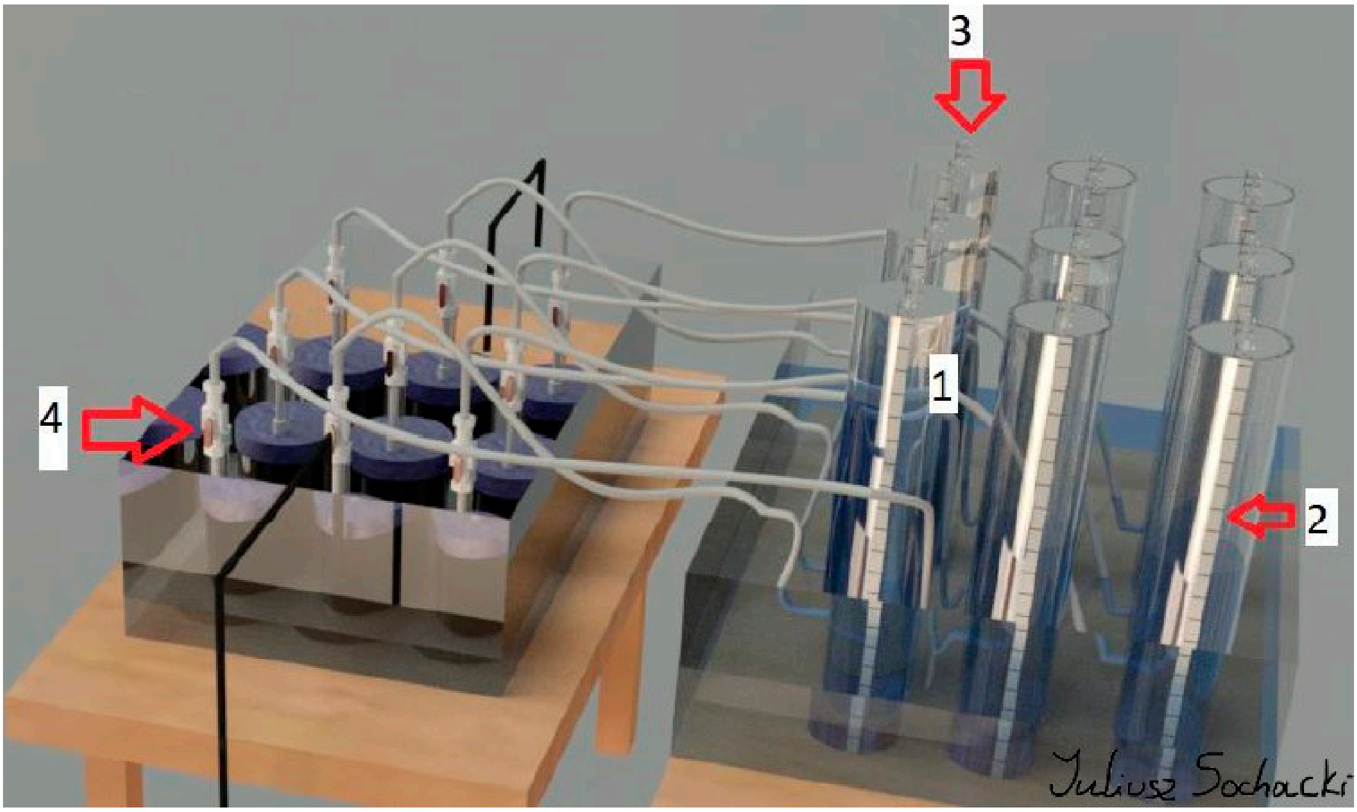

Figure 4. Visualization of the stand for measuring biogas efficiency of batch culture. (1) gas measuring tubes, (2) scale, (3) gas valve, (4) water bath.

2.5. Methodology for Calculating Energy Production

The analysis of the energy and economic balance of a given farm was preceded by the determination of several necessary components, especially in relation to the biogas installation with a cogeneration unit for obtaining heat and electricity from it for commercial purposes.

As input data, it was assumed that the potential biogas plant would run the most popular type of fermentation—methane fermentation in mesophilic conditions. The feedstock for the biogas plant will be cow manure together with agricultural waste/by-products (co-substrate model). Depending on the variant, the biogas plant will have the appropriate power of the cogeneration unit (CHP) and a gas-tight digester (the so-called lagoon), the content of which (digestate) will ultimately be used as fertilizer.

The amount of Ex energy produced (electricity Ee or heat Et) in a biogas installation with a CHP unit was estimated according to Equation (7):

$$E_x = VCH_4 \cdot WCH_4 \cdot \eta_x \text{ [MWh]} \tag{7}$$

where:

VCH_4—methane produced in the fermentation process,
WCH_4—calorific value of methane—9.968 kWh/m^3,
η_x—electric or thermal efficiency of the cogeneration unit.

Estimated power Px (electric Pe or thermal Pt) of the biogas installation was calculated according to Equation (8):

$$P_x = E_x/t \text{ [MW]} \tag{8}$$

where:

t—CHP working time.

Due to the GJ unit adopted and used in heat energy settlements, a conversion factor of −1 MWh to 3.6 GJ was applied in further calculations.

To calculate the power of a given unit, it is necessary to know or predict the working time and efficiency in the production of a given type of energy (electricity or heat). For this reason, it was necessary to assume the average length of operation (for micro and small installations) of the unit in year t amounting to 8200 h and to estimate the efficiency factor a priori. The ηx coefficients are strictly dependent on the operating time, installation load, etc. Therefore, first the operational data encountered in practice were analyzed [13,97–102] and then synthetically presented in Table 1 in relation to the expected power of the installation.

Table 1. Coefficients for energy calculations.

Coefficients	η_e	η_t
Pe < 50 kW	0.18–0.30	0.65–0.50
Pe 50–250 kW	0.30–0.40	0.50–0.46
Pe > 250 kW	0.40–0.43	0.46–0.43

3. Results

The results, as described in the methodology, were divided into several parts. Individual estimates refer to data obtained from a functioning farm, but the way of presenting the results so that they can be easily interpreted is similar to other works on a given subject.

3.1. Streams of Emissions

Individual nitrous oxide and methane emission streams are presented in Table 2.

Table 2. Nitrous oxide and methane emission streams for individual variants.

Parameters	M CH_4	M N_2OD	M N_2OG	M N_2OL
Variant/Unit	Mg CH_4/year		Mg N_2O/year	
M + F	6.82	0.25	0.504	0.0630
M + F + P	1.20	0.13	0.050	0.0019
M + B	0.00	0.00	0.005	0.0001

Upon comparing each variant separately, it is evident that the masses of methane produced by the manure are many times greater than the streams of nitrous oxide (especially in the first two variants). Indeed, when comparing the variants, the differences are even several orders of magnitude apart.

The masses of methane and nitrous oxide streams and the final production of CO_2eq, taking into account the conversion factors listed in the methodology (25 for CH_4 and 298 for N_2O), are presented in Table 3.

Table 3. Annual production of CO_2eq.

Parameters	M CH_4	CO_2eq-CH_4	Sum M N_2O	CO_2eq-N_2O	Sum of CO_2eq
Variant/Unit	Mg CH_4/year	Mg CO_2eq/year	kg N_2O/year	Mg CO_2eq/year	Mg CO_2eq/year
M + F	6.82	170.418	0.819	244.18	414.60
M + F + P	1.20	30.074	0.178	53.16	83.23
M + B	0.00	0.000	0.005	1.54	1.54

In comparing the total masses of CH_4 and N_2O separately for each variant, it is evident that the masses of methane produced by manure are almost 10 times higher, but when converted to CO_2eq, the situation changes and the climate load from nitrous oxide may be three times higher (especially in the first two variants). In turn, comparing the variants with and without a biogas plant (i.e., 1 and 2 with 3), the differences reach even several orders of magnitude apart. It is worth noting that the compaction and covering of the manure (variant M + F + P) reduces the potential climate load (expressed as CO_2eq) by about 5 times.

3.2. Energy and Economic Estimates

In addition to the manure from the 140 dairy cows, the case study farm still had a significant amount of crop by-products. All substrates constituted the feedstock for the biogas plant—the characteristics of individual energy materials are given in Table 4. Biogas and methane yields as well as the share of CH_4 in biogas were determined on the basis of the described sections—research methodology in terms of fresh mass (FM), albeit, only for variants M + B and the same variant enriched only with the GHG aspect.

Table 4. Characteristics of co-substrates and methane efficiency.

Parameters	Dry Mass Content	Methane Efficiency	Used Substrate	Used Substrate	Methane Production
Substrate/Unit	%	m^3·FM/Mg	Mg/year	Mg/d	m^3/year
Manure	15.59	35.82	2811	7.70	100,672
Grass silage	30.76	107.32	370	1.01	39,708
Mix aftercrops	18.66	61.21	530	1.45	32,441
Maize silage	39.19	127.33	345	0.95	43,928
Wheat straw	90.78	240.05	240	0.66	57,612

Based on the presented characteristics, it can be concluded that manure has the largest share in the co-substrate mix—twice as much as the sum of the other components. It is also the material with the highest humidity, so its efficiency in terms of fresh weight is the lowest (about seven times lower than that of wheat straw, the dry weight of which is about 91%). Ultimately, the annual production of methane is over 270,000 cubic meters.

Table 5 shows the input data for the energy and economic balance. It should be noted that the numerical values shown are rounded for clarity.

Table 5. Energy and economic balance parameters.

Parameters	Unit/Variant	M + B
Energetic value of methane W CH_4	MWh/m^3	0.009968
Electrical efficiency ηe	-	0.32
Heat efficiency ηh	-	0.47
Operating time of the CHP unit	h/year	8200
Feed in Tariff	EUR/MWh	195
Heat price	EUR/GJ	29
Cost of Biogas and CHP installation	EUR	712,299
Digestate price	EUR/Mg	23
Substrate mass	Mg/year	4296
Mass reduction during fermentation	Mg	349
Percentage mass reduction	%	8.13
Digestate production	Mg/year	3946

In recent years in European countries (including Poland), support mechanisms have been launched for newly built energy sources (e.g., CHP biogas plants) for ecological reasons. Such a form of support in Poland is the introduction of guaranteed prices for the electricity introduced to the grid—Feed in Tariff (FiT tariff) for small biogas plants (Pe < 0.5 MW) [103]. After converting the exchange rate differences and the calculation formula from the reference price, the value of EUR 195/MWh was adopted for the calculations. Mass reduction during fermentation and percentage mass reduction were calculated on the basis of produced methane and carbon dioxide (main components of biogas) during methane fermentation of co-substrates.

For the given input data, the production of electricity and heat was calculated at 875 MWh/year and 1285 MWh/year, respectively. Powers were also determined, electric and thermal, respectively, as 107 kW and 157 kW (Table 6).

Table 6. Energy performance of a biogas plant with CHP.

Parameters	Unit/Variant	M + B
Electric energy Ee	MWh/year	875
Electric power Pe	kW	107
Heat production Et	MWh/year	1285
Thermal power Pt	GJ	4627
Thermal power Pt	kW	157
Electric energy for own use	%	6
Heat for own needs	%	12

The energy consumption for operating purposes of the entire installation with connections was set at 6% and 12%, respectively, of electricity and heat (these parts of energy do not generate any profit or loss in the balance sheet).

The streams of costs and revenues generated both from dairy production and the investment in biogas plants with a cogeneration unit (investment expenditures and operating costs) are presented in Table 7.

Table 7. Economic data for dairy production and biogas installation.

Parameters	Unit/Variant	M + B
REVENUE		
Revenue from selling produced electricity	EUR	160,489
Revenue from selling generated heat	EUR	115,791
Revenue from selling produced digestate	EUR	88,087
Annual milk production	L/year	342,188
Milk production costs, annual average	EUR/L	0.44
Selling price, annual average	EUR/L	0.45
Revenue from the sale of milk	EUR/year	23,953
COSTS		
Substrate costs		
Manure	EUR/Mg	18
Grass silage	EUR/Mg	49
Mix aftercrops	EUR/Mg	35
Maize silage	EUR/Mg	66
Wheat straw	EUR/Mg	60
Substrate costs in total	EUR	123,608
Running costs		
Service rate	EUR/MWh	4
Service cost	EUR	3907
Cost of technology service	EUR/month	313
Cost of technology service, yearly	EUR/year	2679
Cost of CHP unit service	EUR	4129
Insurance cost	EUR	1674
Cost of hiring personnel		
Level of staff involvement	%	80
Maintenance workers salary	EUR/month	1339
Personnel costs	EUR/year	12,857
Total installation operating costs	EUR/year	148,854
Amortization costs		
Cost of biogas and CHP installation	EUR	712,299
Amortization period	years	10
Interest rate	%	6.75
Cost of amortization	EUR/year	100,247

Data on costs and revenues came directly from the case study farm, own experience and market analysis, which were referred to local scientific and popular publications [10,41,104–109]. In turn, the value of the reference interest rate was adopted on the basis of data published by the National Bank [110].

When checking the farm's financial flows, it turned out that the profit from the sale of milk is slightly more than 1 cent/L (in the last two quarters there has been a significant drop in the purchase price of milk in Poland). Amounts for substrates were included in the costs part because it was assumed that if they were not inputted to the biogas plant, they would be sold at the market price.

Adding up individual financial flows shows how much a given investment can be beneficial for the investor. The results of the profit and loss balances, after taxation, indicate that a biogas installation with a CHP unit, the heat and electricity which will be sold, has a chance to pay itself off in just over 6 years (Table 8).

Table 8. Base economic balance.

Parameters	Unit/Variant	M + B
ECONOMY BALANCE		
Revenue	EUR/year	388,320
Costs	EUR/year	249,101
Profit before tax	EUR/year	139,219
Tax rate	%	18
Profit after tax	EUR/year	114,159
Payback period (PB)	Years	6.24
Return of Capital Employed (ROCE)	%	16.0

Unfortunately, this is frequently not possible; the construction costs are often too high or the recipient (or even their own farm) is not able to receive the amount of heat produced for more than a few months. Assuming the extreme case of no heat collection (beyond the installation's own needs), the actual economic result is much worse than the original (Table 9).

Table 9. Economic balance for different scenarios (excluding revenues from heat).

Parameters	Unit/Variant	M + B
ECONOMY BALANCE (excl. revenues from heat)		
Revenue	EUR/year	248,576
Costs	EUR/year	249,101
Profit before tax	EUR/year	−525
Tax rate	%	18
Profit after tax	EUR/year	−525
Payback period (PB)	Years	negative value
Return of Capital Employed (ROCE)	%	−0.1

The profits from the sale of heat account for approx. two thirds of the profits for electricity; therefore, the lack of this revenue stream means generating minor (EUR 525 per year) losses for the enterprise. However, if at least a few dozen percent of the heat could be collected for the needs of the farm itself, the ROCE and PBP would have a positive value (it would not generate losses).

3.3. Energy and Economic Estimates for Different Variants

If it was necessary to incur costs related to GHG emission allowance, an additional analysis was carried out, additionally taking into account:

- costs related to compacting and covering the manure (variant M + F + P), (Table 10),
- profits from the sale of milk and manure (variant M + F + P and variant M + F),

- 5% weight loss of stored uncompacted and uncovered manure.

Table 10. Compacting and covering cost of farmyard manure.

Parameters	Unit	Value
Compaction and coverage	EUR/m^2	7.0
Sealing foil with additional weight	EUR/m^2	0.50
Number of dairy cows	head	140
Required area for manure slab	m^2/head	2.1
Total compaction and cover costs	EUR/a	2065

For the calculations of total compaction and cover costs, it was assumed that the expenditure of funds and work for compaction and covering (with a load) will cost an average of EUR 7 per year per m^2 (extra work time, fuel, equipment depreciation, etc.), and the cost of the material will amount to approx. 10 years (which is depreciation time adopted for biogas plants)—costs approx. EUR 2.5 per m^2.

The obtained values for individual variants, taking into account the costs of emission allowances and additional costs and revenues (see Table 10), are presented in Table 11.

Table 11. Economic balance for different variants incl. GHG emissions allowance.

Parameter/Variant	M + B + EA	M + F + P + EA	M + F + EA	Unit
Mass of CO_2eq emissions	1.54	83.23	414.60	Mg CO_2eq
Price of carbon emissions allowances	90.90	90.90	90.90	EUR/Mg CO_2eq
Total carbon emissions costs	140	7565	37686	EUR/a
Revenue	330,424	74,140	71,631	EUR/a
Total compaction and cover costs	248,961	2065	0	EUR/a
Profit before tax	81,323	64,509	33,944	EUR/a
Tax rate	18	18	18	%
Profit after tax	66,685	52,898	27,834	EUR/a

Data regarding revenue come from Table 7 and they are the sum of "Revenue from the sale of milk (EUR 23,953)" and the multiplication: Used substrate—manure (2811 Mg per year) from Table 4 and the cost for 1 Mg manure—EUR 18 (Table 7), with the difference that the losses (volatilization, surface runoff, infiltration) of the mass of uncovered manure were estimated at 5% (95% of 2811 Mg/year). Ultimately, it was assumed that all manure produced in the M + F + P + EA and M + F + EA scenarios would be stored and used for own needs, sold or exchanged. Hence, the final revenues from M + F + P + EA amount to EUR 74,140, and from M + F + EA equal EUR 71,631 (95% of 2811 Mg/year). The costs of compaction and covering concerned only the M + F + P + EA variant and amounted to EUR-2065.

If it is necessary to incur costs related to emissions, the greatest economic benefits will come from the M + B + EA option, related to the investment in a biogas installation with a cogeneration unit—almost EUR 67,000 per year. More than 20% less annual profit will be achieved using only the passive protection (compacting and covering) of manure. The least favorable solution is the typical management of manure, which, apart from environmental damage and odors related mainly to ammonia, will bring almost 60% less annual profits for a dairy farm.

4. Discussion

The economic situation of dairy farming on the market is difficult all over the world. The problem of increasing global demand for food is increasing, but is unstable regionally and periodically. Hence, dairy cow breeders must take into account the limits caused by oversupply, or even the need to incur losses. This aspect therefore has a social and political dimension, and given the problems related to emissions from livestock, there is also an ecological aspect. This is particularly evident in calls for limiting the breeding sector, which in recent years has been a fairly common and difficult to compromise issue for decision makers, breeders and, finally, consumers [49]. The solution that would seem to be the only right one due to scientific and technological progress, i.e., with the growing demand for food [111,112], is increasing the unit efficiency of animal production (without increasing the herd), which does not fully reflect the hopes placed. Unfortunately, as research sources show, in order to significantly reduce greenhouse gas (and ammonia) emissions, it is possible either to reduce animal production in general (and thus to reduce food supply with increasing demand) [18,28,113,114], or to develop potential emission streams in a non-standard way.

Many scientific and research reports [49,62,104,115–117] and projects [75–78] indicate that one of the most effective mitigation methods in the case of animal waste is the most frequent and fastest (with the shortest storage period) energy use (biogas plant with CHP). Such actions (on dairy farms), which have been demonstrated in this work in reference to others, lead to, among others:

1. highest farm income and investment indicators,
2. greatest reduction in GHG emissions and odor limitations.

With reference to the first aspect, our study shows that it is possible to accomplish this on this type of family farm. Revenue from electricity production is approx. EUR 20/MWh higher than the average price of electricity in the second quarter of this year (2023) [62]. Even greater revenues would be generated by the sale of heat or through the use of this for the farm's own needs. On the market, the purchase of GJ of energy from fuel for heating purposes ranges from 24 (oil, gas) to 35 (other fuels) EUR [118,119]. In addition, it should be noted that the payback period is slightly longer than 6 years, which is quite a short payback period. Compared to the most competitive and common (for farms) solution in solar panels, assuming that the price of electricity is EUR 180 (the price threshold proposed by the European Commission), the payback of a PV project results in a payback period of five to six years, which is considered favorable [120]. In the case of the presented solution for the construction of a biogas installation with a cogeneration unit, the return does not go much beyond this range, although at a price of approx. EUR 15 per MWh more. In another scientific source, the result of 6 years is also given as very good [121]. For 2022, for various solutions of PV panels, with the amount for electricity lower by several dozen euros, the payback time was over 10 years [122]. In contrast, in the case of biogas solutions recognized as financially advantageous, typically PB values in the range of 5–8 years are typically obtained [123–125]. Regarding micro biogas plants of the variant where investments in land are not required but labor costs are required, a time period of a return of even less than 5 years has been achieved (data, however, come from 8 years ago) [126]. Similar low values were also obtained when taking into account the cost of reducing CO_2-equivalent emissions based on the recast Renewable Energy Directive (RED II) in Hungary [127]. The feedstock for the biogas plant in the reported example was manure and household waste. For this installation, payback periods of 3.6 and 4.4 years and ROCE of 17.7 and 12.8 were estimated (for the amortization period of 10 years). It should be noted, however, that the researcher assumed EUR 328 and EUR 277 per MWh of electricity, respectively, where in our study it was only EUR 195/MWh. On the one hand, it was an installation smaller than the one presented in our study by over one order of magnitude, which is evidenced by the amount of methane produced and the used co-substrates. On the other hand, the estimated investment cost was EUR 8800 per kW of electricity, and the electrical and thermal efficiency coefficients were 45 and 50%, respectively, while for the installation presented in our study, the investment costs were as much as approx. EUR 10,268/kW of electricity with efficiency coefficients of 32% and 47%, respectively. The above-mentioned values have a significant impact on the economic effect; after taking them into account, the overall balance sheet and economic indicators would be similar.

Some estimates show that the introduction of fees for GHG emissions will reduce the average profits of farms by as much as 7.2 percent [70]. Within our study, such losses were estimated at a level of approx. over 20% if the manure was covered and compacted and, if left without any protective treatment, as many as several dozen. The estimated costs in New Zealand after the introduction of fees for CO_2eq emissions (approx. EUR 200 per ton) for an average herd of 414 cows may, in extreme cases, be as much as approx. USD 230,000 per year [128]. Comparable values will be obtained in Poland; assuming the values from the current study for a herd in Poland three times smaller (140 cows) and for almost twice as low fees (less than EUR 91 per ton of CO_2eq), this amount would be approx. EUR 226,120 (this results from the following conversion: $2 \times 3 \times$ EUR 37,686 per year for CO_2eq emissions). However, some national studies have shown that both the lack of subsidies and the decrease in revenues (sometimes by as little as 20%) or the necessary change in substrates may make the investment unprofitable [129]. In the case of this study, such a negative factor could be the introduction of a fee for emissions and their payment, or the need to change substrates, which may contribute to significant operational (and thus financial) problems [130].

Concerning the second aspect, any form of management shortly after manure collection can significantly reduce emissions, as this work and many others have shown [30,49]. In the case of this study, CO_2eq mitigation after the use of a biogas plant would be almost 270 times higher than uncovered and uncompacted manure and 54 times higher than covered and compacted manure. This simple and relatively cheap protective measure allows for almost four times the reduction in emissions compared to standard manure stored in a heap. The reason for this is the low impact on methane emissions from the heap; according to the IPCC [81–83] it is just over 10%, while the values are several dozen times higher in the case of nitrous oxide and ammonia. Similar claims can be found in a study of almost 20 years ago [37], as well as others [131], that showed that compacting and covering manure with plastic sheeting had the potential to reduce NH_3 emissions by more than 90% and nitrous oxide by about 30%. An almost complete reduction in CH_4 emissions as a result of manure management in a biogas plant—at least 90%—has been indicated in many studies [49,62]. Some sources even specify the use of biogas units as sources of avoided CH_4 emissions [132–135].

In addition, it was shown in the work that already as a result of significant losses, primarily from nitrogen compounds, the composition of the digestate may be richer in these nutrients [136–138].

Beyond the aforementioned, the study has revealed that as a result of significant losses from poorly stored manure (oxidation, leachate), primarily from nitrogen compounds, the digestate composition may be even richer in these nutrients. Moreover, if during methane fermentation the reduction in nitrogen and phosphate in post-fermentation manure takes place, it is minimal and lower than its loss from unprotected manure [55,139,140]. In a 2005 study [37], it was found that compaction and covering of manure with foil allows N and K to be retained in the manure heap, providing agronomic benefits. In addition, there are scientific reports that the methane fermentation process allows for a significant reduction in the negative impact of antibiotics present in manure on the soil biocenosis [141,142]. Applying digestate as a crop fertilizer is the most economical option; this approach allows for using the digestate's nutrients and reducing chemical fertilizer costs [143].

5. Conclusions

Since the carbon footprint is already a standard cost component in many industries, it should be expected that in the near future it will also be an element of the economic balance of a dairy farm. This aspect is being raised more and more often due to the need to convert to green milk production, as well as the oversupply of milk on the market and the climate and energy crisis (indirectly also the fertilizer crisis). The farmer, as a future investor, may be forced directly or indirectly (penalties, taxes, reduction in subsidies, etc.) to include fees for carbon dioxide equivalent emission permits in the price of milk. In such a situation, dairy cow breeders will also be covered and this may mean significant costs and, thus, financial losses.

The amount of greenhouse gases emitted during the storage and handling of manure ranges from negligible to the largest sources on dairy farms. If landfilling was excluded, for example by direct use in a biogas plant, greenhouse gas emissions from manure processing would be so low that they could be neglected in the estimates.

Since the use of the mechanism of fees for GHG emissions is a matter of the coming years, regardless of its size and method of calculation, it should be included in the economic estimates of future investments in biogas plants built on farms (including dairy farms).

Most of the dairies, not only in Poland but also almost all over the world, cannot afford to incur expenses for the construction of a complete biogas plant with a cogeneration installation on their own. The growing interest in such solutions has been, is and should be supported by subsidies from government agencies and organizations. In the current situation of falling milk prices, even with subsidized support to offset initial capital investments, small dairy farms often lack the scale necessary to generate a positive return on investment. In the presented study, the farm had a very efficient production system and a large number of productive crops, and was able to purchase additional substrates relatively cheaply, which is not a common phenomenon, especially in Central and Eastern Europe.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The author acknowledges the partners of the Joint Call of the Cofund ERA-Nets SusCrop (Grant N° 771134), FACCE ERA-GAS (Grant N° 696356), ICT-AGRI-FOOD (Grant N° 862665) and SusAn (Grant N° 696231), this work was carried out as part of research at the Poznan University of Life Sciences.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Farm Bureau Financial Services. 4 Uses for Agricultural Waste That Can Save Farmers Money. Available online: https://www.fbfs.com/learning-center/4-uses-for-agricultural-waste-that-can-save-farmers-money (accessed on 8 August 2023).
2. Research and Innovation. Available online: https://ec.europa.eu/research-and-innovation/en/projects/success-stories/all/agricultural-waste-marketable-products (accessed on 8 August 2023).
3. Czekała, W.; Janczak, D.; Cieślik, M.; Mazurkiewicz, J.; Pulka, J. Food Waste Management Using *Hermetia Illucens* Insect. *J. Ecol. Eng.* **2020**, *21*, 214–216. [CrossRef] [PubMed]
4. Shaibur, M.R.; Husain, H.; Arpon, S.H. Utilization of Cow Dung Residues of Biogas Plant for Sustainable Development of a Rural Community. *Curr. Res. Environ. Sustain.* **2021**, *3*, 100026. [CrossRef]
5. Pandyaswargo, A.H.; Jagath Dickella Gamaralalage, P.; Liu, C.; Knaus, M.; Onoda, H.; Mahichi, F.; Guo, Y. Challenges and an Implementation Framework for Sustainable Municipal Organic Waste Management Using Biogas Technology in Emerging Asian Countries. *Sustainability* **2019**, *11*, 6331. [CrossRef]
6. Paranjpe, A.; Saxena, S.; Jain, P. A Review on Performance Improvement of Anaerobic Digestion Using Co-Digestion of Food Waste and Sewage Sludge. *J. Environ. Manag.* **2023**, *338*, 117733. [CrossRef] [PubMed]
7. Frankowski, J.; Czekała, W. Agricultural Plant Residues as Potential Co-Substrates for Biogas Production. *Energies* **2023**, *16*, 4396. [CrossRef]
8. Sonu; Rani, G.M.; Pathania, D.; Abhimanyu; Umapathi, R.; Rustagi, S.; Huh, Y.S.; Gupta, V.K.; Kaushik, A.; Chaudhary, V. Agro-Waste to Sustainable Energy: A Green Strategy of Converting Agricultural Waste to Nano-Enabled Energy Applications. *Sci. Total Environ.* **2023**, *875*, 162667. [CrossRef]
9. Innovative Integrated Approach of Biofuel Production from Agricultural Wastes by Anaerobic Digestion and Black Soldier Fly Larvae-ScienceDirect. Available online: https://www.sciencedirect.com/science/article/abs/pii/S0959652620315420?via%3Dihub (accessed on 14 July 2023).
10. Mazurkiewicz, J. Analysis of the Energy and Material Use of Manure as a Fertilizer or Substrate for Biogas Production during the Energy Crisis. *Energies* **2022**, *15*, 8867. [CrossRef]
11. Teymoori Hamzehkolaei, F.; Amjady, N. A Techno-Economic Assessment for Replacement of Conventional Fossil Fuel Based Technologies in Animal Farms with Biogas Fueled CHP Units. *Renew. Energy* **2018**, *118*, 602–614. [CrossRef]
12. Aguirre-Villegas, H.A.; Larson, R.A. Evaluating Greenhouse Gas Emissions from Dairy Manure Management Practices Using Survey Data and Lifecycle Tools. *J. Clean. Prod.* **2017**, *143*, 169–179. [CrossRef]

13. Ciuła, J.; Kowalski, S.; Generowicz, A.; Barbusiński, K.; Matuszak, Z.; Gaska, K. Analysis of Energy Generation Efficiency and Reliability of a Cogeneration Unit Powered by Biogas. *Energies* **2023**, *16*, 2180. [CrossRef]
14. PMC. Composition and Toxicity of Biogas Produced from Different Feedstocks in California. Available online: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7608650/ (accessed on 5 August 2023).
15. Full, J.; Baumgarten, Y.; Dokur, Y.; Miehe, R.; Sauer, A. Biogas Plants as Hydrogen Production Facilities and Greenhouse Gas Sinks: Technology Comparison, Challenges and Potentials for Carbon Negative Hydrogen Production (HyBECCS). *Procedia CIRP* **2022**, *107*, 185–190. [CrossRef]
16. Hamelin, L.; Naroznova, I.; Wenzel, H. Environmental Consequences of Different Carbon Alternatives for Increased Manure-Based Biogas. *Appl. Energy* **2014**, *114*, 774–782. [CrossRef]
17. Holm-Nielsen, J.B.; Al Seadi, T.; Oleskowicz-Popiel, P. The Future of Anaerobic Digestion and Biogas Utilization. *Bioresour. Technol.* **2009**, *100*, 5478–5484. [CrossRef]
18. Twine, R. Emissions from Animal Agriculture—16.5% Is the New Minimum Figure. *Sustainability* **2021**, *13*, 6276. [CrossRef]
19. Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. *Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*; Gerber, P.J., Food and Agriculture Organization of the United Nations, Eds.; Food and Agriculture Organization of the United Nations: Rome, Italy, 2013; ISBN 978-92-5-107920-1.
20. FAO. News Article: Key Facts and Findings. Available online: https://www.fao.org/news/story/en/item/197623/icode/ (accessed on 22 October 2022).
21. Steinfeld, H.; Wassenaar, T. The Role of Livestock Production in Carbon and Nitrogen Cycles. *Annu. Rev. Environ. Resour.* **2007**, *32*, 271–294. [CrossRef]
22. Rivera, J.E.; Chará, J. CH_4 and N_2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems. *Front. Sustain. Food Syst.* **2021**, *5*, 657936. [CrossRef]
23. Bai, Z.; Ma, L.; Jin, S.; Ma, W.; Velthof, G.L.; Oenema, O.; Liu, L.; Chadwick, D.; Zhang, F. Nitrogen, Phosphorus, and Potassium Flows through the Manure Management Chain in China. *Environ. Sci. Technol.* **2016**, *50*, 13409–13418. [CrossRef]
24. Bai, M.; Flesch, T.; Trouvé, R.; Coates, T.; Butterly, C.; Bhatta, B.; Hill, J.; Chen, D. Gas Emissions during Cattle Manure Composting and Stockpiling. *J. Environ. Qual.* **2020**, *49*, 228–235. [CrossRef]
25. Emissions Impossible: Methane Edition. Available online: https://www.iatp.org/emissions-impossible-methane-edition (accessed on 15 August 2023).
26. Arcipowska, A.; Mangan, E.; Lyu, Y.; Waite, R. 5 Questions about Agricultural Emissions, Answered. 2019. Available online: https://www.wri.org/insights/5-questions-about-agricultural-emissions-answered (accessed on 15 August 2023).
27. Livestock Don't Contribute 14.5% of Global Greenhouse Gas Emissions. Available online: https://thebreakthrough.org/issues/food-agriculture-environment/livestock-dont-contribute-14-5-of-global-greenhouse-gas-emissions (accessed on 15 August 2023).
28. Xu, X.; Sharma, P.; Shu, S.; Lin, T.-S.; Ciais, P.; Tubiello, F.N.; Smith, P.; Campbell, N.; Jain, A.K. Global Greenhouse Gas Emissions from Animal-Based Foods Are Twice Those of Plant-Based Foods. *Nat. Food* **2021**, *2*, 724–732. [CrossRef]
29. Little, S.M.; Benchaar, C.; Janzen, H.H.; Kröbel, R.; McGeough, E.J.; Beauchemin, K.A. Demonstrating the Effect of Forage Source on the Carbon Footprint of a Canadian Dairy Farm Using Whole-Systems Analysis and the Holos Model: Alfalfa Silage vs. Corn Silage. *Climate* **2017**, *5*, 87. [CrossRef]
30. Thoma, G.; Popp, J.; Shonnard, D.; Nutter, D.; Matlock, M.; Ulrich, R.; Kellogg, W.; Kim, D.S.; Neiderman, Z.; Kemper, N.; et al. Regional Analysis of Greenhouse Gas Emissions from USA Dairy Farms: A Cradle to Farm-Gate Assessment of the American Dairy Industry circa 2008. *Int. Dairy J.* **2013**, *31*, S29–S40. [CrossRef]
31. Siegl, S.; Hagenbucher, S.; Niggli, U.; Riedel, J. Addressing Dairy Industry's Scope 3 Greenhouse Gas Emissions by Efficiently Managing Farm Carbon Footprints. *Environ. Chall.* **2023**, *11*, 100719. [CrossRef]
32. Rotz, C.A. Modeling Greenhouse Gas Emissions from Dairy Farms. *J. Dairy Sci.* **2018**, *101*, 6675–6690. [CrossRef] [PubMed]
33. Naranjo, A.; Johnson, A.; Rossow, H.; Kebreab, E. Greenhouse Gas, Water, and Land Footprint per Unit of Production of the California Dairy Industry over 50 Years. *J. Dairy Sci.* **2020**, *103*, 3760–3773. [CrossRef] [PubMed]
34. Peterson, C.B.; Mitloehner, F.M. Sustainability of the Dairy Industry: Emissions and Mitigation Opportunities. *Front. Anim. Sci.* **2021**, *2*, 760310. [CrossRef]
35. Baldini, C.; Gardoni, D.; Guarino, M. A Critical Review of the Recent Evolution of Life Cycle Assessment Applied to Milk Production. *J. Clean. Prod.* **2017**, *140*, 421–435. [CrossRef]
36. Mazurkiewicz, J.; Mazur, A.; Mazur, R.; Chmielowski, K.; Czekała, W.; Janczak, D. The Process of Microbiological Remediation of the Polluted Słoneczko Reservoir in Poland: For Reduction of Water Pollution and Nutrients Management. *Water* **2020**, *12*, 3002. [CrossRef]
37. Chadwick, D.R. Emissions of Ammonia, Nitrous Oxide and Methane from Cattle Manure Heaps: Effect of Compaction and Covering. *Atmos. Environ.* **2005**, *39*, 787–799. [CrossRef]
38. Dewes, T. Effect of pH, Temperature, Amount of Litter and Storage Density on Ammonia Emissions from Stable Manure. *J. Agric. Sci.* **1996**, *127*, 501–509. [CrossRef]
39. Manure Coverage | Climate Technology Centre & Network. Tue, 11 August 2016. Available online: https://www.ctc-n.org/technologies/manure-coverage (accessed on 18 August 2023).

40. Sneath, R.W.; Beline, F.; Hilhorst, M.A.; Peu, P. Monitoring GHG from Manure Stores on Organic and Conventional Dairy Farms. *Agric. Ecosyst. Environ.* **2006**, *112*, 122–128. [CrossRef]
41. Mazurkiewicz, J. Energy and Economic Balance between Manure Stored and Used as a Substrate for Biogas Production. *Energies* **2022**, *15*, 413. [CrossRef]
42. Khan, R.Z.; Müller, C.; Sommer, S.G. Micrometeorological Mass Balance Technique for Measuring CH_4 Emission from Stored Cattle Slurry. *Biol. Fertil. Soils* **1997**, *24*, 442–444. [CrossRef]
43. Khan, M.U.; Usman, M.; Ashraf, M.A.; Dutta, N.; Luo, G.; Zhang, S. A Review of Recent Advancements in Pretreatment Techniques of Lignocellulosic Materials for Biogas Production: Opportunities and Limitations. *Chem. Eng. J. Adv.* **2022**, *10*, 100263. [CrossRef]
44. Husted, S. Seasonal Variation in Methane Emission from Stored Slurry and Solid Manures. *J. Environ. Qual.* **1994**, *23*, 585–592. [CrossRef]
45. Saggar, S. Estimation of Nitrous Oxide Emission from Ecosystems and Its Mitigation Technologies. *Agric. Ecosyst. Environ.* **2010**, *136*, 189–191. [CrossRef]
46. Tittonell, P.; Rufino, M.C.; Janssen, B.H.; Giller, K.E. Carbon and Nutrient Losses during Manure Storage under Traditional and Improved Practices in Smallholder Crop-Livestock Systems—Evidence from Kenya. *Plant Soil* **2010**, *328*, 253–269. [CrossRef]
47. Manure Nutrient Losses. Available online: https://water.unl.edu/article/animal-manure-management/manure-nutrient-losses (accessed on 18 August 2023).
48. Ramin, M.; Chagas, J.C.; Smidt, H.; Exposito, R.G.; Krizsan, S.J. Enteric and Fecal Methane Emissions from Dairy Cows Fed Grass or Corn Silage Diets Supplemented with Rapeseed Oil. *Animals* **2021**, *11*, 1322. [CrossRef]
49. Grossi, G.; Goglio, P.; Vitali, A.; Williams, A.G. Livestock and Climate Change: Impact of Livestock on Climate and Mitigation Strategies. *Anim. Front.* **2019**, *9*, 69–76. [CrossRef]
50. Mathot, M.; Lambert, R.; Stilmant, D.; Decruyenaere, V. Carbon, Nitrogen, Phosphorus and Potassium Flows and Losses from Solid and Semi-Solid Manures Produced by Beef Cattle in Deep Litter Barns and Tied Stalls. *Agric. Syst.* **2020**, *178*, 102735. [CrossRef]
51. Köninger, J.; Lugato, E.; Panagos, P.; Kochupillai, M.; Orgiazzi, A.; Briones, M.J.I. Manure Management and Soil Biodiversity: Towards More Sustainable Food Systems in the EU. *Agric. Syst.* **2021**, *194*, 103251. [CrossRef]
52. Schott, C.; Cunha, J.R.; van der Weijden, R.D.; Buisman, C. Innovation in Valorization of Cow Manure: Higher Hydrolysis, Methane Production and Increased Phosphorus Retention Using UASB Technology. *Chem. Eng. J.* **2023**, *454*, 140294. [CrossRef]
53. Nutrient Management. Available online: https://www.gov.uk/government/statistics/farm-practices-survey-february-2023-greenhouse-gas-mitigation/nutrient-management (accessed on 16 August 2023).
54. Report. Available online: https://www.eca.europa.eu/ECAPublications/SR-2023-19/SR-2023-19_EN.pdf (accessed on 16 August 2023).
55. Lim, T. Increasing the Value of Animal Manure for Farmers. Available online: https://www.ers.usda.gov/webdocs/publications/106089/ap-109.pdf?v=3816.3 (accessed on 16 August 2023).
56. Petersen, S.O.; Blanchard, M.; Chadwick, D.; Del Prado, A.; Edouard, N.; Mosquera, J.; Sommer, S.G. Manure Management for Greenhouse Gas Mitigation. *Animal* **2013**, *7*, 266–282. [CrossRef] [PubMed]
57. Nutrients. Available online: https://agriculture.ec.europa.eu/sustainability/environmental-sustainability/low-input-farming/nutrients_en (accessed on 17 August 2023).
58. CAP 2023-27: €9bn Strategic Plans for Croatia, Slovenia and Sweden Approved—Insight EU Monitoring. Available online: https://portal.ieu-monitoring.com/editorial/cap-2023-27-e9bn-strategic-plans-for-croatia-slovenia-and-sweden-approved/392055/?utm_source=ieu-portal (accessed on 17 August 2023).
59. Villarroel-Schneider, J.; Höglund-Isaksson, L.; Mainali, B.; Martí-Herrero, J.; Cardozo, E.; Malmquist, A.; Martin, A. Energy Self-Sufficiency and Greenhouse Gas Emission Reductions in Latin American Dairy Farms through Massive Implementation of Biogas-Based Solutions. *Energy Convers. Manag.* **2022**, *261*, 115670. [CrossRef]
60. Pilarska, A.A.; Pilarski, K.; Adamski, M.; Zaborowicz, M.; Cais-Sokolińska, D.; Wolna-Maruwka, A.; Niewiadomska, A. Eco-Friendly and Effective Diatomaceous Earth/Peat (DEP) Microbial Carriers in the Anaerobic Biodegradation of Food Waste Products. *Energies* **2022**, *15*, 3442. [CrossRef]
61. Kowalczyk-Juśko, A.; Pochwatka, P.; Mazurkiewicz, J.; Pulka, J.; Kępowicz, B.; Janczak, D.; Dach, J. Reduction of Greenhouse Gas Emissions by Replacing Fertilizers with Digestate. *J. Ecol. Eng.* **2023**, *24*, 312–319. [CrossRef] [PubMed]
62. United States Environmental Protection Agency. Practices to Reduce Methane Emissions from Livestock Manure Management. Available online: https://www.epa.gov/agstar/practices-reduce-methane-emissions-livestock-manure-management (accessed on 23 October 2022).
63. Frankowski, J.; Zaborowicz, M.; Dach, J.; Czekała, W.; Przybył, J. Biological Waste Management in the Case of a Pandemic Emergency and Other Natural Disasters. Determination of Bioenergy Production from Floricultural Waste and Modeling of Methane Production Using Deep Neural Modeling Methods. *Energies* **2020**, *13*, 3014. [CrossRef]
64. Sefeedpari, P.; Pudełko, R.; Jędrejek, A.; Kozak, M.; Borzęcka, M. To What Extent Is Manure Produced, Distributed, and Potentially Available for Bioenergy? A Step toward Stimulating Circular Bio-Economy in Poland. *Energies* **2020**, *13*, 6266. [CrossRef]
65. Mazurkiewicz, J.; Marczuk, A.; Pochwatka, P.; Kujawa, S. Maize Straw as a Valuable Energetic Material for Biogas Plant Feeding. *Materials* **2019**, *12*, 3848. [CrossRef]

66. Wentzel, S.; Joergensen, R.G. Effects of Biogas and Raw Slurries on Grass Growth and Soil Microbial Indices. *J. Plant Nutr. Soil Sci.* **2016**, *179*, 215–222. [CrossRef]
67. Zheng, X.; Fan, J.; Cui, J.; Wang, Y.; Zhou, J.; Ye, M.; Sun, M. Effects of Biogas Slurry Application on Peanut Yield, Soil Nutrients, Carbon Storage, and Microbial Activity in an Ultisol Soil in Southern China. *J. Soils Sediments* **2016**, *16*, 449–460. [CrossRef]
68. Bougnom, B.P.; Niederkofler, C.; Knapp, B.A.; Stimpfl, E.; Insam, H. Residues from Renewable Energy Production: Their Value for Fertilizing Pastures. *Biomass Bioenergy* **2012**, *39*, 290–295. [CrossRef]
69. Kupryaniuk, K.; Oniszczuk, T.; Combrzyński, M.; Czekała, W.; Matwijczuk, A. The Influence of Corn Straw Extrusion Pretreatment Parameters on Methane Fermentation Performance. *Materials* **2020**, *13*, 3003. [CrossRef] [PubMed]
70. What Farmers Need to Know about Emissions Pricing. Available online: https://news.anz.com/content/news/new-zealand/posts/2022/06/What-farmers-need-to-know-about-emissions-pricing (accessed on 20 August 2023).
71. Costs and Benefits to Agriculture from Climate Change Policy. Available online: https://www.card.iastate.edu/iowa_ag_review/summer_09/article1.aspx (accessed on 20 August 2023).
72. Pricing Agricultural Emissions. Available online: https://www.dairynz.co.nz/environment/agricultural-greenhouse-gases/pricing-agricultural-emissions/ (accessed on 20 August 2023).
73. Dairy, vs. Plant-Based Milk: What Are the Environmental Impacts? Available online: https://ourworldindata.org/environmental-impact-milks (accessed on 20 August 2023).
74. Emissions Recommendations "Would Penalise Farmers". Available online: https://www.nzherald.co.nz/the-country/news/emissions-recommendations-would-penalise-farmers/X3UKEBLEDSW67QMSRFNH64GQCQ/ (accessed on 20 August 2023).
75. Home. Available online: https://www.milkey-project.eu/ (accessed on 22 July 2023).
76. Home—MELS. Available online: https://www.mels-project.eu/ (accessed on 2 December 2022).
77. Climate Care Cattle Farming Systems | The Project. Available online: https://cccfarming.eu/ (accessed on 22 July 2023).
78. DairyMix. Available online: https://www.eragas.eu/en/eragas/research-projects/dairymix.htm (accessed on 22 July 2023).
79. Owens, J.L.; Thomas, B.W.; Stoeckli, J.L.; Beauchemin, K.A.; McAllister, T.A.; Larney, F.J.; Hao, X. Greenhouse Gas and Ammonia Emissions from Stored Manure from Beef Cattle Supplemented 3-Nitrooxypropanol and Monensin to Reduce Enteric Methane Emissions. *Sci. Rep.* **2020**, *10*, 19310. [CrossRef]
80. Mazur, K.; Roman, K.; Wardal, W.J.; Borek, K.; Barwicki, J.; Kierończyk, M. Emission of Harmful Gases from Animal Production in Poland. *Environ. Monit. Assess.* **2021**, *193*, 341. [CrossRef] [PubMed]
81. IPCC-TFI. Publications. Available online: https://www.ipcc-nggip.iges.or.jp/public/2019rf/ (accessed on 19 August 2023).
82. IPCC. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Available online: https://www.ipcc.ch/report/2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed on 30 October 2022).
83. Calvin, K.; Dasgupta, D.; Krinner, G.; Mukherji, A.; Thorne, P.W.; Trisos, C.; Romero, J.; Aldunce, P.; Barrett, K.; Blanco, G.; et al. *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed.; Core Writing Team, Lee, H., Romero, J., Eds.; IPCC: Geneva, Switzerland, 2023.
84. UNFCCC. Poland. 2022 National Inventory Report (NIR). Available online: https://unfccc.int/documents/461818 (accessed on 30 July 2023).
85. Podlasek, A.; Koda, E.; Vaverková, M.D. The Variability of Nitrogen Forms in Soils Due to Traditional and Precision Agriculture: Case Studies in Poland. *Int. J. Environ. Res. Public Health* **2021**, *18*, 465. [CrossRef] [PubMed]
86. Measuring Emissions: Detailed Guide 2020. Available online: https://environment.govt.nz/publications/measuring-emissions-detailed-guide-2020/ (accessed on 23 October 2022).
87. Wang, C.; Amon, B.; Schulz, K.; Mehdi, B. Factors That Influence Nitrous Oxide Emissions from Agricultural Soils as Well as Their Representation in Simulation Models: A Review. *Agronomy* **2021**, *11*, 770. [CrossRef]
88. Nadan, M.K.; Baroutian, S. Prospective of Pretreatment and Anaerobic Digestion of Dairy Cow Manure in Fiji. *J. Chem. Technol. Biotechnol.* **2023**, *98*, 1584–1597. [CrossRef]
89. EU Carbon Permits. 2023 Data-2005–2022 Historical-2024 Forecast-Price-Quote. Available online: https://tradingeconomics.com/commodity/carbon (accessed on 19 August 2023).
90. EU ETS Allowances Auctioned by Country 2022. Available online: https://www.statista.com/statistics/1329545/eu-ets-allowances-auctioned-or-sold-by-country/ (accessed on 1 August 2023).
91. Pracownia Ekotechnologii. Available online: https://ekolab.up.poznan.pl/en (accessed on 1 August 2023).
92. VDLUFA. Demonstration Des Quantitativen Nachweises von Salmonellen. Available online: https://www.vdlufa.de/schulungen-2/schulungen-2013/demonstration-des-quantitativen-nachweises-von-salmonellen/ (accessed on 30 October 2022).
93. KTBL: Ktbl.De. Available online: https://www.ktbl.de/ (accessed on 30 October 2022).
94. VDI 4630. *Fermentation of Organic Materials—Characterization of the Substrate, Sampling, Collection of Material Data, Fermentation Tests*; VDI Verein Deutscher Ingenieure e.V.: Düsseldorf, Germany, 2016.
95. Standards, E. DIN 38414-8. Available online: https://www.en-standard.eu/din-38414-8-german-standard-methods-for-the-examination-of-water-waste-water-and-sludge-sludge-and-sediments-group-s-determination-of-the-amenability-to-anaerobic-digestion-s-8/ (accessed on 1 August 2023).
96. Mazurkiewicz, J. The Biogas Potential of Oxytree Leaves. *Energies* **2022**, *15*, 8872. [CrossRef]
97. Slavica, P.; Ivica, M.; Dragica, R.; Milios, J.; Slobodan, J.; Vladislav, N. Testing the Energy Efficiency of CHP Engines and Cost-Effectiveness of Biogas Plant Operation. *IET Renew. Power Gener.* **2023**, *17*, 555–562. [CrossRef]

98. Electricity and Heat Production from Biogas CHP: Discover Technologies. Available online: https://www.biogasworld.com/news/biogas-chp-discover-technologies/ (accessed on 20 August 2023).
99. Pourmovahed, A.; Opperman, T.; Lemke, B. Performance and Efficiency of a Biogas CHP System Utilizing a Stirling Engine. In Proceedings of the International Conference on Renewable Energies and Power Quality, Las Palmas de Gran Canaria, Spain, 13–15 April 2011; pp. 202–207. [CrossRef]
100. Hakawati, R.; Smyth, B.M.; McCullough, G.; De Rosa, F.; Rooney, D. What Is the Most Energy Efficient Route for Biogas Utilization: Heat, Electricity or Transport? *Appl. Energy* **2017**, *206*, 1076–1087. [CrossRef]
101. CHP-Biogas El.Power 12kW + HeatPower 25kW Cogeneration Combined Heat and Power (CHP) Combined Heat and Power (CHP) [SP12B]-€33,440.00: Profil.Fi, Pumps, Ventilation, Pipes, Valves, Boilers, under Floor Heating, Hybrid Solar Heating, Heat Pumps, Pumps, Generators. Available online: https://profil.fi/generators-and-chp-biogas-gensets/el-power-75kw-heatpower-14-kw-ng-generator (accessed on 20 August 2023).
102. Mazlan, M.; Najafi, G.; Hoseini, S.S.; Mamat, R.; Alenzi, R.A.; Mofijur, M.; Yusaf, T. Thermal Efficiency Analysis of a Nanofluid-Based Micro Combined Heat and Power System Using CNG and Biogas. *Energy* **2021**, *231*, 120870. [CrossRef]
103. A Guide to Support for Polish Renewable Energy Sources Following the 2018 Amendments | Global Law Firm | Norton Rose Fulbright. Available online: https://www.nortonrosefulbright.com/en-pl/knowledge/publications/5932a770/a-guide-to-support-for-polish-renewable-energy-sources-following-the-2018-amendments (accessed on 30 October 2022).
104. Pochwatka, P.; Kowalczyk-Juśko, A.; Sołowiej, P.; Wawrzyniak, A.; Dach, J. Biogas Plant Exploitation in a Middle-Sized Dairy Farm in Poland: Energetic and Economic Aspects. *Energies* **2020**, *13*, 6058. [CrossRef]
105. Mikrobiogazownia Rolnicza—Dla Kogo i Za Ile? Available online: http://wiescirolnicze.pl/technika/mikrobiogazownia-rolnicza-dla-kogo-i-za-ile/ (accessed on 5 August 2023).
106. Małe Biogazownie—Jakie są Koszty i co Dają Rolnikom? Available online: https://www.tygodnik-rolniczy.pl/rolnictwo/pieniadze/male-biogazownie-jakie-sa-koszty-i-co-daja-rolnikom-2383690 (accessed on 5 August 2023).
107. Beba, J. Mała Czy Duża Biogazownia Rolnicza? Available online: https://www.topagrar.pl/articles/eventy/mala-czy-duza-biogazownia-rolnicza/ (accessed on 5 August 2023).
108. Mikrobiogazownia w Każdej Wsi? *Magazyn Biomasa*. 2023. Available online: https://magazynbiomasa.pl/mikrobiogazownia-w-kazdej-wsi-teraz-to-mozliwe/ (accessed on 5 August 2023).
109. Szwaja, S. Analiza Opłacalności Ekonomicznej Mikrobiogazowni Rolniczej. Available online: https://www.cire.pl/pliki/2/2017/13___szwaja___mikrobiogazownia_v1__rec16a.pdf (accessed on 5 August 2023).
110. Podstawowe Stopy Procentowe NBP. Available online: https://nbp.pl/polityka-pieniezna/decyzje-rpp/podstawowe-stopy-procentowe-nbp/ (accessed on 5 August 2023).
111. Piwowar, A. Farming Practices for Reducing Ammonia Emissions in Polish Agriculture. *Atmosphere* **2020**, *11*, 1353. [CrossRef]
112. Roubík, H.; Mazancová, J. Suitability of Small-Scale Biogas Systems Based on Livestock Manure for the Rural Areas of Sumatra. *Environ. Dev.* **2020**, *33*, 100505. [CrossRef]
113. Eisen, M.B.; Brown, P.O. Rapid Global Phaseout of Animal Agriculture Has the Potential to Stabilize Greenhouse Gas Levels for 30 Years and Offset 68 Percent of CO_2 Emissions This Century. *PLoS Clim.* **2022**, *1*, e0000010. [CrossRef]
114. Hayek, M.N.; Harwatt, H.; Ripple, W.J.; Mueller, N.D. The Carbon Opportunity Cost of Animal-Sourced Food Production on Land. *Nat. Sustain.* **2021**, *4*, 21–24. [CrossRef]
115. Díaz-Vázquez, D.; Alvarado-Cummings, S.C.; Meza-Rodríguez, D.; Senés-Guerrero, C.; de Anda, J.; Gradilla-Hernández, M.S. Evaluation of Biogas Potential from Livestock Manures and Multicriteria Site Selection for Centralized Anaerobic Digester Systems: The Case of Jalisco, México. *Sustainability* **2020**, *12*, 3527. [CrossRef]
116. Achinas, S.; Willem Euverink, G.J. Rambling Facets of Manure-Based Biogas Production in Europe: A Briefing. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109566. [CrossRef]
117. Zareei, S. Evaluation of Biogas Potential from Livestock Manures and Rural Wastes Using GIS in Iran. *Renew. Energy* **2018**, *118*, 351–356. [CrossRef]
118. Energetyki, U.R. Cena Energii Elektrycznej w Kontraktach Dwustronnych w Trzecim Kwartale Roku Wyniosła Ponad 615 zł/MWh. Available online: https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/10583,Cena-energii-elektrycznej-w-kontraktach-dwustronnych-w-trzecim-kwartale-roku-wyn.html (accessed on 30 October 2022).
119. Energetyki, U.R. Rynek Energii: Średnia Cena Energii Elektrycznej z Rozliczeń Wytwórców w Ramach Grup Kapitałowych w II Kwartale 2023 r. Available online: https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/11215,Rynek-energii-srednia-cena-energii-elektrycznej-z-rozliczen-wytworcow-w-ramach-g.html (accessed on 1 August 2023).
120. Wind, Solar Payback Times under a Year in Some Parts of World, Says Rystad. Available online: https://www.pv-magazine.com/2022/10/14/wind-solar-payback-times-under-a-year-in-some-parts-of-world-says-rystad/ (accessed on 22 August 2023).
121. Hanley, S. Switching The World to Renewable Energy Will Cost $62 Trillion, But The Payback Would Take Just 6 Years. Available online: https://cleantechnica.com/2022/09/06/switching-the-world-to-renewable-energy-will-cost-62-trillion-but-the-payback-would-take-just-6-years/ (accessed on 22 August 2023).
122. Kessler, W. Comparing Energy Payback and Simple Payback Period for Solar Photovoltaic Systems. *E3S Web. Conf.* **2017**, *22*, 80. [CrossRef]

123. Vilas Bôas, T.F.; Barros, R.M.; Pinto, J.A.; dos Santos, I.F.S.; Lora, E.E.S.; Andrade, R.V.; Tiago Filho, G.L.; Almeida, K.A.; de Oliveira Machado, G. Energy Potential from the Generation of Biogas from Anaerobic Digestion of Olive Oil Extraction Wastes in Brazil. *Clean. Waste Syst.* **2023**, *4*, 100083. [CrossRef]
124. Tan, V.W.G.; Chan, Y.J.; Arumugasamy, S.K.; Lim, J.W. Optimizing Biogas Production from Palm Oil Mill Effluent Utilizing Integrated Machine Learning and Response Surface Methodology Framework. *J. Clean. Prod.* **2023**, *414*, 137575. [CrossRef]
125. Furtado, L.A.; Guerreiro Ribeiro, S.; Pradelle, F.; Parise, J.A.R. Modeling and Techno-Economic Analysis of a Hybrid Sugarcane Plant Fed by Vinasse Biogas and Bagasse Surplus for Electricity Generation. *J. Clean. Prod.* **2023**, *413*, 137511. [CrossRef]
126. Wresta, A.; Andriani, D.; Saepudin, A.; Sudibyo, H. Economic Analysis of Cow Manure Biogas as Energy Source for Electricity Power Generation in Small Scale Ranch. *Energy Procedia* **2015**, *68*, 122–131. [CrossRef]
127. Agar, D.A.; Athanassiadis, D.; Pavelka, B.J. The CO_2 Cutting Cost of Biogas from Humanure and Livestock Manure. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102381. [CrossRef]
128. How Much Will Agricultural Emissions Cost Farmers?—NZ Herald. Available online: https://www.nzherald.co.nz/the-country/news/how-much-will-agricultural-emissions-cost-farmers/X3YCMNKI2CA6R4LBQ2KFFYJFVU/ (accessed on 22 August 2023).
129. Klimek, K.; Kapłan, M.; Syrotyuk, S.; Bakach, N.; Kapustin, N.; Konieczny, R.; Dobrzyński, J.; Borek, K.; Anders, D.; Dybek, B.; et al. Investment Model of Agricultural Biogas Plants for Individual Farms in Poland. *Energies* **2021**, *14*, 7375. [CrossRef]
130. Czubaszek, R.; Wysocka-Czubaszek, A.; Banaszuk, P. Importance of Feedstock in a Small-Scale Agricultural Biogas Plant. *Energies* **2022**, *15*, 7749. [CrossRef]
131. Oenema, O.; Oudendag, D.; Velthof, G.L. Nutrient Losses from Manure Management in the European Union. *Livest. Sci.* **2007**, *112*, 261–272. [CrossRef]
132. Eggemann, L.; Rau, F.; Stolten, D. The Ecological Potential of Manure Utilisation in Small-Scale Biogas Plants. *Appl. Energy* **2023**, *331*, 120445. [CrossRef]
133. Oehmichen, K.; Thrän, D. Fostering Renewable Energy Provision from Manure in Germany—Where to Implement GHG Emission Reduction Incentives. *Energy Policy* **2017**, *110*, 471–477. [CrossRef]
134. O'Keeffe, S.; Franko, U.; Oehmichen, K.; Daniel-Gromke, J.; Thrän, D. Give Them Credit-the Greenhouse Gas Performance of Regional Biogas Systems. *GCB Bioenergy* **2019**, *11*, 791–808. [CrossRef]
135. Lansche, J.; Müller, J. Life Cycle Assessment of Energy Generation of Biogas Fed Combined Heat and Power Plants: Environmental Impact of Different Agricultural Substrates. *Eng. Life Sci.* **2012**, *12*, 313–320. [CrossRef]
136. Czekała, W.; Jasiński, T.; Grzelak, M.; Witaszek, K.; Dach, J. Biogas Plant Operation: Digestate as the Valuable Product. *Energies* **2022**, *15*, 8275. [CrossRef]
137. Czekała, W.; Nowak, M.; Bojarski, W. Characteristics of Substrates Used for Biogas Production in Terms of Water Content. *Fermentation* **2023**, *9*, 449. [CrossRef]
138. Czekała, W.; Jasiński, T.; Dach, J. Profitability of the Agricultural Biogas Plants Operation in Poland, Depending on the Substrate Use Model. *Energy Rep.* **2023**, *9*, 196–203. [CrossRef]
139. Scarlat, N.; Fahl, F.; Dallemand, J.-F.; Monforti, F.; Motola, V. A Spatial Analysis of Biogas Potential from Manure in Europe. *Renew. Sustain. Energy Rev.* **2018**, *94*, 915–930. [CrossRef]
140. Mazurkiewicz, J. Loss of Energy and Economic Potential of a Biogas Plant Fed with Cow Manure due to Storage Time. *Energies* **2023**, *16*, 6686. [CrossRef]
141. Hosseini Taleghani, A.; Lim, T.-T.; Lin, C.-H.; Ericsson, A.C.; Vo, P.H. Degradation of Veterinary Antibiotics in Swine Manure via Anaerobic Digestion. *Bioengineering* **2020**, *7*, 123. [CrossRef]
142. Zubair, M.; Li, Z.; Zhu, R.; Wang, J.; Liu, X.; Liu, X. The Antibiotics Degradation and Its Mechanisms during the Livestock Manure Anaerobic Digestion. *Molecules* **2023**, *28*, 4090. [CrossRef]
143. Campos, J.L.; Crutchik, D.; Franchi, Ó.; Pavissich, J.P.; Belmonte, M.; Pedrouso, A.; Mosquera-Corral, A.; Val del Río, Á. Nitrogen and Phosphorus Recovery From Anaerobically Pretreated Agro-Food Wastes: A Review. *Front. Sustain. Food Syst.* **2019**, *2*, 91. [CrossRef]