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Review

The Synergy Potential of Energy and Agriculture—The Main Directions of Development

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Abstract: The development of renewable energy is increasingly blurring the line between the energy and agricultural sectors. Decarbonizing agriculture is essential for the development of sustainable development principles. This can be achieved in essentially the two following ways: by reducing fuel consumption and by making the livestock sector more efficient. This review sets out options for contributing to these two elements. The review sets the stage for a smoother synergy process, whereby waste generated in agriculture is fully utilized to strengthen farms. In conducting the review, the methods of scientific induction and deduction were used. One of the key elements is the recycling of the waste generated into biomethane. This biomethane in turn is used as a fuel for tractors and as a means of providing energy for farms. The production of biomethane or biogas can lead to decentralization of the energy system, with farms becoming less or completely independent from external energy supplies. At the same time, synergies with other forms of energy are being created. These make it possible to increase the income of farms by adding a new activity of supplying energy to other consumers.

Keywords: synergies effects; renewable energy; sustainable development; agriculture

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1. Introduction

As the energy system expands, more and more stakeholders are involved. The decentralization of the energy system is no longer a surprising factor, but synergies with agricultural activities are becoming more and more apparent. Farmers face the huge challenge of climate change. Livestock farming is increasingly recognized as environmentally damaging, but there is still a lack of technology to decarbonize this sector. Manure-to-energy conversion is already advanced and cost-effective, but daily emissions from livestock are still a problem. In addition, unsustainable tillage also leads to higher emissions instead of fixing carbon in the ground. Food waste is another major problem, both from the processing of the produce grown and from the non-consumption of the finished product. Manure treatment plants can also help to solve this problem.

The synergy between renewable energy and agriculture involves integrating renewable energy systems into agricultural operations to create mutual benefits for both sectors. This relationship is crucial for advancing sustainable practices, enhancing energy security, and addressing the global challenge of climate change. Farms, especially those involved in the processing of produce, are becoming increasingly large energy consumers. There are different solutions that can help farms to decarbonize their operations while having a positive impact on the environment. Farms can host solar photovoltaic (PV) systems, either on the ground or integrated into buildings, such as on barn roofs. This not only provides a clean energy source for the farm's operations but can also generate additional income through the sale of excess electricity. Agrivoltaic systems, which combine solar energy production with crop cultivation, can enhance land use efficiency and reduce water evaporation from crops, improving agricultural productivity [1]. This solution requires the lowest time and financial costs, and with flexible planning synergies can be achieved—solar cells can be the basis for new carports or used as roofs on new buildings. For existing buildings, additional measurements are required to maximize efficiency. The solutions analyzed below require more lead time and the initial investment is relatively higher than for solar power plants. Wind turbines can be installed on agricultural land with minimal disruption to farming activities. This allows farmers to diversify income through leasing land for wind energy production or owning turbines directly. The income from wind energy can help to stabilize a farm's income, which is otherwise often subject to variability due to price fluctuations and weather conditions [2]. Wind energy is favorable to farms because those farms that own the land can choose the most suitable area for a wind turbine project. However, the coordination of wind turbine projects takes a relatively long time. During this period, the cost-effectiveness and grid capacity characteristics of the wind farm may change substantially.

There are other alternatives that are not widely used because of their geographical characteristics. These solutions can be used to complement the technologies presented above. Geothermal energy can be used for heating greenhouses, enabling year-round cultivation in cooler climates. This use of renewable heat sources can reduce dependency on fossil fuels and lower greenhouse gas emissions, contributing to more sustainable agricultural practices [3]. An essential element of this technology is a stable electricity supply to support the geothermal water recovery process. This makes it necessary to pursue solar energy development alongside geothermal energy development. This aspect and the lack of practical application of geothermal energy have led to a reduction in the use of this type of energy production on farms. Another technology that can be used on farms is hydropower. Small-scale hydropower systems can be used to generate electricity or irrigate land. Dams are an appropriate remedy to control floods and maintain or increase agricultural production in the farm. This can provide power for irrigation systems and other farm operations, improving energy access and efficiency in rural areas [4]. However, there are a couple of nuances to consider when looking at the use of hydropower in agriculture. Firstly, the ethical aspects of hydropower are increasingly being addressed due to its significant impacts on the environment and fish migration. Secondly, the potential of hydropower is only available to a small proportion of farms that are located close to watery rivers. Thirdly, the development of new hydropower plants, particularly in the European Union and the USA, is highly regulated. The information presented suggests that the main trends in farm decarbonization relate to wind, solar, and biomass.

However, the clearest potential for synergies relates to the use of biomass and bioenergy. This is particularly true for the use of waste from agricultural activities. Agriculture is generally very wasteful and therefore also a contributor to greenhouse gas emissions. The issue of methane production from livestock on farms should be viewed as a positive, presenting the opportunity to create green energy and help reduce greenhouse effects. The main challenge is to develop technologies that are cost-effective and affordable for family farms to develop their energy activities [5]. Agriculture produces various by-products, such as crop residues, manure, and other organic waste, which can be converted into bioenergy. This process can provide a renewable energy source while reducing waste and greenhouse gas emissions. Anaerobic digestion of agricultural waste can produce biogas for heating, electricity, and fuel, subsequently contributing to farm sustainability and energy self-sufficiency. The possible sites of implementation that have a clear potential are those of the large farms and industries that continually need energy. These include not only existing farms with biological gas potential but also farms which are to be built in the near future. The main drawback of biogas production is its limited production potential in urban areas. However, this opens up good opportunities to develop the production in regional areas due to the abundance of raw materials [6]. One of the biggest challenges for the future is the treatment of food waste. The developed world is witnessing an increasing food waste dynamic. Consumer awareness can help reduce food waste, but it will not eliminate the problem of treating the waste that is already generated. Farms can make a significant contribution to converting food waste into energy or gas. A key element of this is biogas production capacity. New supply chains can be created alongside the use of on-farm waste to feed urban food waste into farm-managed biogas reactors. This would improve the possibility of producing high quality biogas, thus allowing for increased farm income from energy sales. In addition, the material obtained from the recycling of the waste would be suitable for fertilization of crops. Another challenge is less-developed countries. Previous research showed a positive relationship between CO_2 emissions and real GDP, non-renewable energy consumption, and agricultural value added in the long run [7]. A lack of cost-effective technologies is holding back the progress of decarbonization in agriculture. Other research shows that per capita output and RE have negative relationship, related to carbon emissions, while per capita non-renewable energy and agriculture exert positive effects on carbon emissions [8]. This research investigated the BRICS countries. Too slow progress in developing countries will make it difficult to decarbonize the sector. Even more, the growing agricultural production in these countries creates the assumption that the scale of environmental problems will only grow.

Previous research papers have only analyzed certain conceptual aspects of energy, with less consideration paid to the potential synergies between technologies. The articles recognize the key factor that renewable energy can help reduce CO_2 emissions from agriculture [9–11]. However, other key aspects are dealt with in a piecemeal manner. On the one hand, there are studies that look at the possible links between the two concepts [12,13]. Nevertheless, these studies deal with some generic aspects, while the climate impacts of the decarbonization of agriculture have not yet been assessed in sufficient depth. There are studies that look at circular economy alternatives in agriculture using renewable energy [14]. However, the concept of renewable energy in agriculture has not yet been fully developed as there is no clear strategic thinking to consistently direct resources towards for decarbonizing the agricultural sector. This paper outlines the key synergies that would enable a coherent path towards decarbonization. The main problem is how to seamlessly integrate energy and climate change mitigation activities into the structure of different farm sizes. As small farms are one of the most vulnerable sectors of the economy, their integration into decarbonization activities must be carried out in a responsible manner which makes the best use of the resources already available. The novelty of the paper is related to the clearly identified opportunities for farms to both comply with the principles of sustainable development and to generate additional income from energy activities without substantial material investment. Novelty is shaped by the identification of synergistic effects. It structures the opportunities for farms to achieve emission reductions with a conservative level of investment. Exploiting synergies speeds up efforts and makes decarbonization activities cheaper. At present, efforts to find ways to change energy solutions in agriculture are struggling. As a result, the level of progress is relatively lower. This paper presents integrated solutions that focus on both farm and community development. The focus is on directions that would not only meet the energy impacts of farms but also enable them to sell energy on the market. In the case of livestock farms, a clear alternative to fossil fuels emerges in the form of biomethane produced in biogas reactors. It can be used to power specially adapted tractors or other implements that currently use diesel. The resulting double effect—reduced pollution on farms and the use in machinery—would lead to significant reductions in harmful gas emissions in the short term. The aim of this paper is to identify the main synergies between the energy sector and agriculture that would increase the economic viability of farms. It includes the analysis of wind, solar energy, and biogas/biomethane integration into the daily activity of farms. Information in this article is current for the developed countries in Europe, North America and Australia, which have strong orientation to renewable energy production, a stable law basis, and existing programs for farms' decarbonization.

2. The Necessity of Renewable Energy for the Decarbonization of Farms

As the impacts of climate change become more acute, there is a need to broaden the scope for decarbonization. There is a growing consensus that decarbonization of the agriculture sector is inevitable. This process can be pursued in several ways. It is necessary to manage the waste from animals which is generated in livestock farms, considering both the environmental and economic aspects. However, there is another problem: the need to reduce daily emissions from livestock. This can be achieved by producing functional feed that is easier to digest. This would reduce the daily release of gases into the environment, while also reducing the amount of feed wasted. On crop farms, the trend towards reducing emissions is more varied. The first step is to optimize fuel consumption by moving away from plowing and towards direct drilling technologies. Reducing pesticide use can also help to reduce pollution. However, the production and use of renewable energy is a key factor in decarbonization. Renewable energy systems can significantly reduce agricultural greenhouse gas (GHG) emissions through substitution of fossil fuel-based energy sources, energy efficiency, and agriculture using waste to generate the energy. To maximize success, key synergies need to be identified.

The processing of agricultural by-products and waste in biogas reactors is necessary in order to reduce the negative impact on the environment. On the one hand, the use of these materials would reduce the use of coal and fossil fuels, while eliminating the possibility of biological materials simply rotting in the open, releasing energy [15]. On the other hand, biogas production must be carried out responsibly, without the inclusion of food-grade materials [16]. This challenge can be solved by cooperatives of several farmers or by creating separate cooperatives focused on biogas production. Another opportunity to decarbonize the environment is related to more active use of biomass. Currently, a large part of the biomass comes from forests, and it is often not possible to check whether waste or high added value wood is being burned. To avoid the burning of wood suitable for industry and for the better use of less productive areas, promotion of agroforestry is necessary. Such a solution would allow for an increase in the volume of carbon stored in the land while also providing economic benefits to farmers [17]. This solution may be appropriate in Asia, where deforestation is a major problem. It is assumed that this will enable the achievement of climate change mitigation goals [18]. India, one of the largest countries in the region, uses agroforestry to achieve climate goals and support farmers' economic viability [19]. Another important aspect is that it helps to promote biodiversity [20]. In any case, the most important thing to do on the path of decarbonization is to implement complex solutions. This will create the conditions to prevent resource waste and contribute more effectively to the goals of stopping climate change.

Different technologies, when combined together, can enable the efficient use of waste from farms while reducing the need for fossil fuels. Energy production can be carried out on a large scale (to sell part of the energy) or in an optimal mode (to produce energy and hot water for the farm). In all cases, renewable energy contributes to the efforts of farms to reduce the level of climate change impacts. The choice of technology is a particularly important aspect for farms as a significant proportion of farms are small family farms. Their resource constraints make it necessary to have clear investment priorities. Moreover, the direction of investment varies according to the structure of the farm. Key aspects of farm decarbonization are as follows:

➢ Solar photovoltaic (PV) panels and solar energy systems can power agricultural operations, irrigation systems, and factories. It can reduce their carbon footprint and reduce the environmental impact of their operations [21]. The technology is particularly effective when used in conjunction with energy storage batteries [22]. The farms use different buildings, which together allow for synergies to be achieved simultaneously by using solar panels on the roof. When new buildings are built, they should be designed to maximize solar potential. With the development of the battery market, the energy produced by solar panels can be stored cost-effectively in on-farm energy storage facilities. Solar energy forms new alternatives for activities. One of these is aeroponics, the operation of which requires electricity. The advantage of solar energy is that it can be integrated into greenhouses [23]. It is argued that solar energy can make a particularly big impact in the global south where there is a lack of stable sources of energy production [24]. Table 1 provides a structured overview of the characteristics of on-farm solar PV development based on the prevailing energy situation in Europe. For the preparation of the article, a preliminary survey was carried out among five solar PV developers in the Baltic states and Poland. The cost of development is differentiated by the scale of the operation—larger farms can build larger capacity plants, thus reducing the cost of construction. Larger plants allow them to cover the entire consumption demand, but in terms of relative size, they sell less electricity than small farms. In both solar and wind power, the small scale of operations will force smaller farms to sell energy on a spot basis rather than under a power purchase agreement (PPA), which requires large and stable production volumes.

Table 1. Possibilities to develop solar energy power plants in farms.

	Small Farms	**Large Farms**
Development price per kW, EUR	1000	700
Energy consumption in the farm, %	20	50
Electricity for selling, %	80	50
Selling regime	Market prices	PPA

➢ Wind farms located on or near farmland can provide a clean, renewable source of electricity for agricultural operations, thereby reducing the need for coal, natural gas, and oil-based electricity GHG emissions directly associated with on-farm energy use [25]. Developing wind energy capacity can create synergies with other developers: by cooperating, faster construction speeds can be achieved, with less impact on the soil. Energy storage in batteries is essential. However, it is agreed that the synergy between wind energy and farm operations is problematic enough. This is because the state-of-the-art wind energy technologies available for an average farm are redundant [26]. The large amount of energy produced would not be used on the farm unless the production of the final product was also carried out there. These solutions are more suitable for agro-industry, and not for a medium-sized farm, because in the latter case the necessary costs for the adaptation and efficient use of such a power plant require much greater synergistic gains. This is would only be possible if a certain part of the land managed by the farm was leased to wind power developers [27,28]. Table 2 provides a structured overview of the characteristics of on-farm wind power development based on the prevailing energy situation in Europe. For the preparation of the article, five wind farm developers in the Baltic states and Poland were preliminarily surveyed. Wind power development is more expensive than solar power and more complicated. Often small farms cannot even develop a wind project. Differentiated development costs for small farms are possible if they install cheaper, second-hand power plants. There are opportunities for farms to sell more electricity on the market, but due to gaps in the legal framework this may not be possible in all cases.

Table 2. Possibilities to develop wind energy power plants in farms.

	Small Farms	**Large Farms**
Development price per kW, EUR	1000–2000	1500
Energy consumption in the farm, %	10	30
Electricity for selling, %	90	70
Selling regime	Market prices	PPA

These two types of energy can be compared with each other since they are suitable for development on land areas managed by farmers. Due to the already established practice of developing such power plants, it is possible to single out essential elements that are relevant both for the farm and the region. Table 3 presents a comparison of the main characteristics relevant to the farm. The table shows the complexity of the situation and how it is necessary to weigh-up both the initial investment and subsequent costs.

Table 3. Characteristics of wind and solar energy in farms.

Type	**Need of Land**	**Need of Capital**	**Efficiency, %**	**Usage for Farm**	**Need of Service**
Wind	Little	High	>50	Complicated	Necessary
Solar	Great	Low	~28	Suitable	Annual

Next to these types of energy production, there are already tested technologies whose interaction with the agricultural sector is relatively well studied. However, these solutions are constantly being improved to achieve better economic and environmental results. Using these energy resources together with the latest energy efficiency technologies, a farm can significantly reduce its operating costs. The following renewable energy solutions suitable for farms:

➢ Bioenergy production: The conversion of agricultural waste (e.g., crop residues, manure) into bioenergy (biogas and biofuel) through processes such as anaerobic digestion and biomass gasification helps to manage waste and reduces emissions from decomposition. The potential of this bioenergy source replaces fossil fuels in heat, electricity generation, and transport [29]. The potential for bioenergy on farms is greatest in the short term—organic waste that is converted into energy can form the basis of energy production on farms. As the cost of more advanced technologies decreases, small farms will have the opportunity to install solar and wind energy capacity, as well as energy storage facilities, more cost-effectively.

- Carbon sequestration: Some energy crops can sequester carbon in their biomass and soil, further reducing GHG emissions. However, total life cycle emissions and land use changes resulting from bioenergy cropping need to be considered to ensure that it provides environmental benefits [30]. Carbon retention in soil grows with fermented organic matter.
- Energy efficiency improvements: Renewable energy systems are often technological improvements that increase the energy efficiency of the farm. Energy efficiency means that less energy is required, further reducing the company's overall GHG emissions [31]. Energy efficiency can be developed in several ways. Firstly, an energy audit is needed to identify areas of energy waste. By identifying the sources of waste, investments are directed towards eliminating them. Once these objectives have been achieved, additional investments in energy production can be considered.
- In geothermal fields, this energy can be used for greenhouses and other agricultural areas. Geothermal energy produces carbon-free heat and energy, helping to reduce GHG emissions from agriculture [32]. The high cost of geothermal energy technology means that it is only suitable for large, high value-added farms. The use of geothermal water inevitably requires the creation of electricity generation capacity, otherwise the potential of green production will be only partially exploited.
- Small hydroelectric systems can be installed in agricultural water systems, such as irrigation systems and dams. These systems provide a renewable source of electricity with very low GHG emissions compared to fossil fuel energy production [33]. However, due to ethical concerns and the loss of land suitable for farming, small hydropower is increasingly underdeveloped in developed countries.

Looking at the situation of both small and large farms, it can be concluded that the use of renewable energy would help to solve the complex problems of pollution generated by farms. According to the structured information, two directions of change can be distinguished: long and short term. In the long term, it is necessary to focus on technologies that not only ensure high energy productivity but also maintain an appropriate level of energy efficiency. In order to achieve these goals, it is necessary to look for technologies on a large scale, thus creating conditions for the development of agriculture. The search for technologies can be promoted with one-time support focused on raising qualifications and identifying the need for technologies [34]. Energy system monitoring measures avoid situations where energy is wasted because of certain isolated problems. Energy power management will also help to improve the efficiency of the farm's energy system. The development of energy storage technologies will bring about a fundamental change for farms by using the energy generated by surplus production to meet the needs of farms during the night. In the short term, the development of bioenergy initiatives is a key factor in a farm's success. The treatment of various animal and plant waste streams would generate large amounts of energy. This energy would enable the energy needs of the farm to be met, with the surplus being sold on the market. Bioenergy activities are characterized by their stability of production: with sufficient waste potential, production can be continuous. The liquid material generated after production is used to fertilize fields. The potential for synergies between energy and agricultural activities using biomass is explored in more detail.

3. Biogas and Biomethane Potential in the Agriculture Sector

The potential of bioenergy essentially lies in the recycling of waste into other materials for energy recovery. The energy can be one of three types—electricity, heat, or biomethane gas. Farms processing agricultural products may require all three types of energy. Biomethane is the most promising type of bioenergy as it can be used as a fuel for tractors. The biomethane concept is best developed in the agricultural machinery sector. In principle, biomethane has no other environmentally friendly substitutes for tractors.

The main potential for bioenergy lies in biomethane. The extraction of this gas from organic waste has created a breakthrough in the energy sector, reducing the impact of natural gas and diesel on agriculture. Biomethane is a higher value-added product than electricity and heat, with fewer renewable substitutes. Although biomethane development technologies are more expensive, they are more marketable due to the uniqueness of the product. It is noted that the main market for biomethane development is Europe. Biomethane production is being strongly promoted through the EU Green Deal initiatives. Biomethane production in Europe has grown exponentially, driven by the industry's commitment to carbon emissions and energy security. In 2021, Europe reached a record number of biomethane plants, with a total of 1023 sites. This expansion represents a significant step towards decarbonization of the EU economy [35]. Biomethane can also be produced by industrial companies that process cereal products. The main factor for the development of biomethane is the possibility to connect to main gas pipelines. This allows for the sale of treated biomethane on the market, creating the conditions for a cross-border biomethane sales market. This is driving the rapid expansion of the biomethane industry on the continent. The European Biogas Association (EBA) and Gas Infrastructure Europe (GIE) revealed that the number of biomethane plants increased by almost 30% compared to the previous phase of their biomethane map. This increase helps biogas production to scale up to reach of the European Commission's target of 35 billion cubic meters by 2030. It emphasizes the promotion of sectoral efforts, as outlined in the REPowerEU framework. This objective aims to enhance the EU's energy security and to increase the uptake of biomethane [36]. If the forward-looking plans come to fruition, a large part of food waste will be recycled into energy, and the production of natural fertilizers will reach a level that can compete significantly with chemical fertilizers. Also, biomethane production in Europe increased from 31 terawatt-hours (TWh) or 2.9 billion cubic meters (bcm) in 2020 to 37 TWh or 3.5 bcm in 2021, marking a 20% increase in the broader trend. Building biomethane has more emphasis than the biogas segment, and this shift is expected to continue over the next decade. Biomethane's versatility as an energy carrier makes it suitable for a variety of industries such as transportation, infrastructure, electricity, and heating [37]. For the European Union, much greater investment in biomethane promotion is foreseen in the future to encourage more farms to join renewable energy activities. The influence of industries processing organic materials must also be emphasized. For these companies, incentive instruments are also being developed to accelerate the start-up of biomethane production. However, these activities are not yet available in all EU countries. This is due to an incomplete legal framework, which does not in all cases allow for the direct supply of purified biogas to national gas pipelines. Projections suggest that the combined biogas and biomethane sector could more than double from 18.4 BCM by 2021 to around 35–45 BCM by 2030. By 2050, at least, production should increase fivefold from the current level to 95–167 BCM qualifies. Such growth would represent a substantial portion of the EU's gas consumption, highlighting biomethane's potential to cover a significant part of the energy demand by 2050 [37]. This aspect shows that biomethane is an important part of the renewable energy agenda. Farmers extracting biomethane could become an important part of the energy transformation, while at the same time extracting biomethane would provide them with the opportunity to generate additional income from spin-off activities. In case of biogas, there is one significant challenge. In order to achieve sustainable biogas production, it is necessary to create a sustainable value chain that will allow the transformation of waste into energy. This is related to the failure to supply products suitable for food-to-biogas reactors, the delivery of waste to them, and the creation of the necessary legal acts [38].

Figure 1 shows the potential for energy recovery from bio-waste. Bioenergy activities have an important impact on the climate by preventing the release of methane, which is extremely harmful to the environment, from the waste treated. The main bioenergy processes are related to biogas production. Biogas production is based on anaerobic digestion. In this case, it is possible to mix different organic wastes, thereby increasing the biogas production. Concentrated biogas production avoids the development of pollution hotspots while also providing the basis for positive economic impacts. Figure 1 shows the potential for fertilizer generation. Organic fertilizers are an important advantage of biogas production as the resulting concentrate is regarded as an environmentally friendly material. This allows farmers to improve their performance without damaging the environment. This fertilizer allows the soil to be enriched, thus returning useful nutrients to the soil. A decentralized gasification solution is one of the potential technologies for the production of biomass and bioenergy using agricultural waste (especially in the food industry). This provides a sustainable alternative to fertilizers for agro-ecosystems and biogas production from anaerobic digestion is a win–win strategy where animals and crop producers can perform an edible waste function and help with energy supply issues, avoiding groundwater contamination, odors, and greenhouse gas emissions [39]. These solutions would help solve a big problem of recent times—environmental pollution. In the case of the EU, agriculture generates about 50% of all energy costs, of which 31 percent consists of diesel [40]. There are several nuances to be resolved in the bioenergetics cycle above. Firstly, the delivery of waste and the removal of organic fertilizers are currently carried out using fossil-fueled vehicles. Tractors are also based on fossil fuels. Some of the biogas treated can be used to power tractors or trucks, but these technologies are relatively underdeveloped. The biomethane produced in biogas reactors is cleaned and then fed into tractors designed to use biogas. This avoids regulatory loopholes compared to the supply of biomethane via trunk pipelines. The European Union is promoting R&D activities to further develop the technology to produce such tractors. Existing biogas plants which produce heat and electricity must be converted to biomethane production plants through the construction of gas cleaning filters. These actions would help to achieve a reduction in pollution of the sector. There are more synergies. The harvest residues can be used to make fuel briquettes, which in turn would reduce the need for wood for burning. This is relevant for poorer regions where deforestation is the only fuel alternative [41].

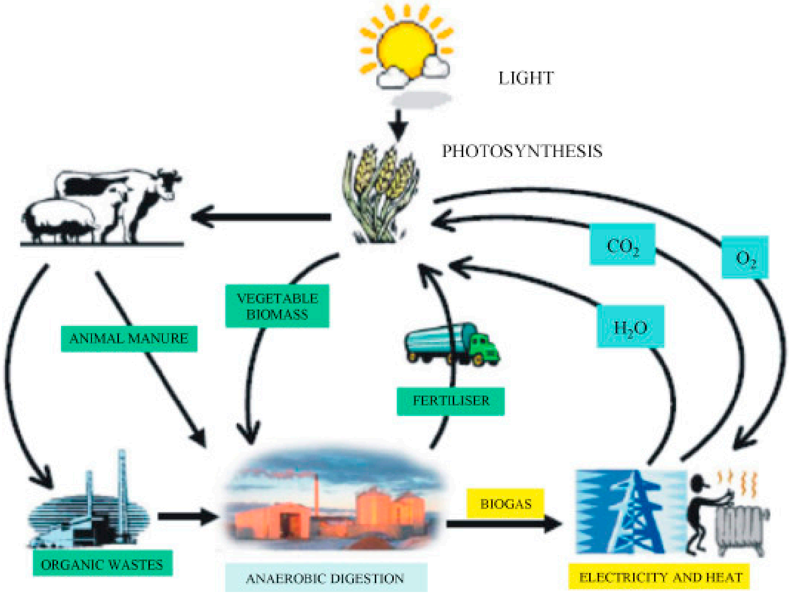

Figure 1. Bioenergy cycle—energy sources and end products (reprinted from ref. [42]).

The focus on bioenergy must go beyond environmental concerns. Recycling bio-waste generates significant economic and social benefits. From an economic point of view, it offers farms the opportunity to generate more income and reduce energy costs. Socially, new jobs can be created in servicing biogas reactors. In addition, the quality of life of neighbors is improved as the environment is no longer polluted by bio-waste and the impact of unpleasant odors is reduced and concentrated. In addition, it is necessary to emphasize energy conservation initiatives. They can be organizational, technical, technological, based on energy, based on selection, or be activities presented in the context of each direction [43].

Recycling organic waste has enormous synergy potential, transforming the agricultural and energy sectors, as well as people's daily lives. With sufficient infrastructure, the conditions are ripe for decarbonizing the transport, heating, ventilation, and electricity generation sectors. This is linked to several principles, the change in which would allow a significant expansion of agricultural activities:

- ➢ Manure Management: Conventional and family farms produce a lot of by-products which can cause environmental damage if not managed properly. Anaerobic digestion (AD) systems can treat these by-products, reduce odors, pathogens, and potential water damage, and produce biogas for on-farm use or sale. This combination can sustain the farm regularly and reduce greenhouse gas emissions [44]. Processing manure into gas and liquid fertilizer will allow for better exploitation of animal waste. This will generate economic benefits and have a positive impact on the climate. Family farms could also benefit from this opportunity—cooperative manure processing capacity would create energy and fertilizer that would be returned to the farm in different fractions.
- ➢ Crop Residue Utilization: Agricultural residues, such as grass and corn stalks, can be difficult to manage, often burned or left to decompose, releasing greenhouse gases. Providing these residues with anaerobic digestion technologies enables farms to evolve the way these organisms turn into energy, ensuring that carbon emissions generate additional revenue and reduce emissions [45]. In this case, the infrastructure used is similar to that used for manure processing. This creates further synergies as biogas plants can be developed by more than just livestock farms. Farm and crop waste can be mixed together to produce energy.
- ➢ Integrated Food and Energy Systems: Both of the above systems are combined in an integrated system that allows the farm to be self-sufficient in energy production. The main axis of integration is the on-farm consumption of the energy produced. Electricity can be used for day-to-day farm operations, heat can help dry crop production, and cleaned gas can be used for tractors, thus avoiding the use of fossil fuels [46]. Such plants have a lower capacity than conventional plants because they are used to meet the needs of the farms. However, they allow farms to be decarbonized as the energy production would offset the pollution from livestock and some equipment. At the same time, this activity would protect farms from fluctuations in energy prices—the surplus energy produced can be stored in batteries and production operations can be carried out according to the dynamics of energy prices.
- ➢ Renewable Energy Production: If commercial energy production activities are carried out on the farm, there are several options for energy outlets. This depends on the infrastructure development in the region where the farm is located [47]. In this case, the potential of biogas is highlighted. First, the latest technology, biomethane, must be mentioned. This type of energy can be used on a particularly large scale, as the gas is routed through trunk pipelines [48,49]. It can then be used by both domestic and business customers. In the absence of transmission or venting infrastructure, conventional electricity and heat production is possible. Biomethane production

provides a solution to a pressing problem: as natural gas consumption declines, a large part of the trunk pipelines will be unsuitable for further operations. The potential for biomethane production would allow the infrastructure to be used in the interim period, to be replaced later by equipment suitable for hydrogen export.

- Community Biogas Projects: Community energy projects have significant untapped potential. Here, public, and private actors, as well as farmers, can work in a cooperative way. This would make it possible to manage bio-waste generated in cities and on farms [50]. This measure would create jobs in regions that are often economically vulnerable. This unlocks the social synergy potential of the agriculture and energy sector, which would benefit not only the region but also the country. In the latter case, the impact is seen through reduced spending on social benefits as well as the tax flow generated by new economic activities. Meanwhile, it is important to take into account the political context. Previous research shows that economic growth holds a long-run causality with financial development, total reserves, energy use, renewable energy use, and agriculture value addition on GDP per capita only in politically free countries [21]. Even earlier studies suggest that developing countries should not adopt energy saving solutions at all [51,52]. This can make it difficult for community initiatives in that part of the world where processes are controlled centrally.

In particular, there is little mention of the social benefits of energy projects. Regions, especially those dominated by agriculture, are less economically developed than areas developing in the industrial or service sectors. Increasing energy efficiency is important now. Earlier studies revealed that with a one percent increase in agricultural energy costs, the level of environmental pollution increases by 0.008 percent [53]. Decentralization of the energy system would strengthen the regions, as a large amount of new energy generation capacity would create the preconditions for new economic activities. This would also help prevent power outages. In case of supply disruptions, the competitiveness of such farms may decline [54]. Decentralized systems can ensure continuous energy supply for such processes as the freezing or cooling of products, incubation of young animals, drying of products, etc. For developing countries that are constantly faced with energy supply disruptions, renewable energy may be the only adequate alternative. A key condition for decentralization is that the allocation of grid capacity is properly regulated to avoid situations where the full production potential is not used. Reserving grid capacity for farms ensures that the system is properly decentralized and oriented towards the promotion of community projects. Increasing the consumption of RE in agriculture is closely related to the farm parameters [55]. Different RE utilization solutions apply to farms of different sizes. However, this requires not only investments, but also a change in operational approach. It will not be enough without the consistent application of innovations. Synergies between different activities could also be represented graphically. It is agreed that reducing CO_2 emissions from farms should be the primary objective of decarbonization activities in rural areas. There are now visible trends that in the installation of, say, biogas production capacity, the components of artificial intelligence, remote monitoring, robots, and emissions management will inevitably appear. This will allow for better containment of harmful gases while creating economic value. At the same time, this creates conditions for the development of smart agriculture [56]. This would avoid a situation in the future where agriculture becomes one of the main emitters. Figure 2 presents the different agricultural alternatives, with a primary focus on smart solutions. Based on these alternatives, the integration of energy solutions would make a significant contribution to curbing the consequences of climate change.

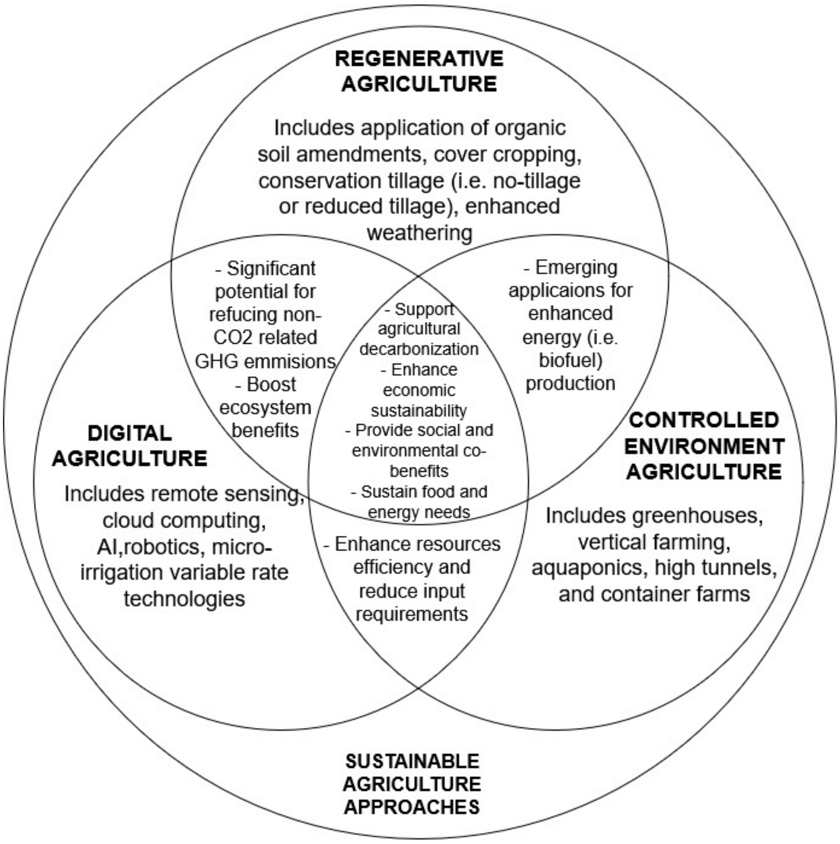

Figure 2. Shared principles of climate-smart agriculture among digital agriculture, regenerative agriculture, and controlled environment agriculture approaches (reprinted from ref. [57]).

Figure 2 shows three pillars of sustainable agriculture. Their impact and the specific area of operation depend on the area of operation, the size of the farm, the development concept chosen, and the receptivity to technology. Finding the right balance between all these technologies ensures the decarbonization of farms. However, the figure does not sufficiently illustrate the positive impact of energy solutions on decarbonization. Moreover, there is no mention of the fact that global change can help farms to substantially increase their competitiveness while diversifying their sources of income. The application of the principles of sustainable agriculture would ensure the controlled production of biogas when non-food materials are used for its production. The application of innovations makes sense not only for organic, but also for conventional farms—this would allow for energy and fertilizer costs to reduce (precision agriculture, electric agrodrones, and crop analysis using AI). This would reduce the need for fossil fuels and increase the possibilities for the farm to supply itself with the produced biogas. This paper highlights the fact that the development of on-farm energy solutions is essential for the implementation of the principles of sustainable development, which will have positive spill-over effects such as the qualitative growth of family farms, the development of local supply chains, and the strengthening of regions.

Summarizing the information provided about the use of biogas in farms, it is necessary to compare the different advantages and disadvantages of using biogas in farms. Before farms make investment decisions, it is necessary to clearly know the quantities and directions of use of the produced energy. The comparative information in Table 4 identifies the main risks that may arise if the farm makes an incorrect investment decision.

Table 4. Possibilities of different biogas technologies in farms.

	Advantages	Disadvantages	Source
Biogas for energy	Non-polluting production preparation for the market is ensured, The ability to meet the farm's energy needs, Emergence of new branches of business, Forming natural fertilizers, The possibility of processing by-products and natural wastes.	Energy production is almost uncompetitive compared to wind and solar, Lack of innovation in the sector, Small farm risks using food grade products.	[58–62]
Biomethane production	A more demanded product in the market, Option to replace fossil fuels in tractors, Forming natural fertilizers. The possibility of processing by-products and natural wastes.	Necessity of development of grids, Significantly more expensive infrastructure, It is necessary to build the filters for gas and tanks are required to store gas. More expensive equipment maintenance, A large, regional scale of activity is necessary.	[63–67]

To achieve universal synergy modeling, it is necessary to distinguish a typical farm model in which renewable energy solutions will be applied. Several studies have established positive causal relationships between farms and the competitiveness of RE compared to non-renewable resources [68]. Meanwhile, there is a clear lack of RE progress in the world. The main challenge is how to find legal and investment regulations that would allow the development of RE faster and without subsidies. A farm can combine several different technologies, but the analysis of scientific literature has clearly shown that biogas reactors are the essential axis of agricultural decarbonization. They can either contain recycled animal waste or use certain other raw materials (grass not suitable for silage, food waste, etc.). Small farms can take advantage of the cooperation option and manage one biogas rector together. In the latter case, the economic benefit would be generated by selling the energy, as dividing it between owners can be difficult from an infrastructure point of view. Additional sales income would especially help in this matter if the main activity of the farm was unprofitable in the current year. The use of biogas on farms is particularly extensive. They can be used for electricity production, heat for greenhouses in the cold season, grain drying, as well as for industrial needs—product processing and silage preparation for self or commercial purposes. Since heat is a by-product of biogas in the case of electricity production, its responsible use can create significant added value for farms. There is also the opposite option—farms that do not have the ability to use a lot of heat can make a pointless investment from an economic point of view. In this case, it is necessary to look for directions for heat consumption both inside and outside.

In the case of using a biogas reactor, it is desirable that the farm develops animal husbandry activities. This would make it possible to obtain by-products, which would later be used as fertilizer. The use of crop production waste alone would be pointless as there is a risk that raw materials suitable for food would have to be used for biogas production. In this case, it is appreciated that a farm having its own biogas power plant would be profitable if they have at least 1 MW energy power [69]. Otherwise, cooperation between different farmers is necessary. A fundamental decision is which technology to choose to achieve the goals of the farm or the cooperative. If the farm is located near gas mains, it can produce biomethane [70,71]. However, in this case it would become difficult to use the gas independently, since the introduction of two technologies would be unprofitable. Another technology allows the production of electricity and heat on the basis of cogeneration. This technology could be used not only in the farms directly, but also in the grain or animal food processing factories. [72–74]. The main nuance is that it is not possible to produce one type of energy if the farm only needs its own electricity. Thus, the need to have a source of heat consumption arises. Not every farm has the ability to consume heat independently, so this creates an opportunity to inefficiently use the created energy production infrastructure. Figure 3 presents a broader interpretation. The basis of biogas activity is related to anaerobic digestion. It is a natural process that uses microorganisms to degrade four-phase (hydrolytic, fermentative, acetogenic, and methanogenic) compounds in the absence of oxygen, producing a high-CH4 gas known as biogas. Benefits include odors, pathogenicity, and greenhouse gases (GHG) emissions from agriculture [75]. The associated risks of air and water pollution can be reduced by better systems such as sealed digester storage and outer shoes, which may require planning. However, crop digestion to produce biogas for dairy products is harmful to the environment, and in any case represents an inefficient strategy for GHG mitigation compared to other crop-based bioenergy options such as miscanthus heating sphere. In addition, bioenergy crops produced on dairy farms displace inputs such as wheat, soybean, and flour and its extracts. There is a high risk that increased demand for food will lead to land use changes, potentially leading to significant increases in GHG emissions. [76]. In addition, the component of energy security appears: biogas production allows for the decentralization of production, thus not only replacing fossil fuels, but also avoiding imports from politically hostile countries [77]. These systems in agricultural waste management reduce waste loads, generate bioenergy, and generate nutrients while powering vehicles and production, among others.

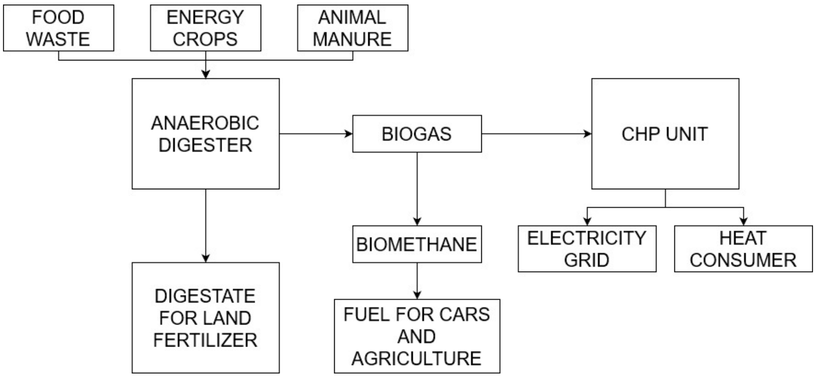

Figure 3. Schematic of farm-scale anaerobic digestion plant (reprinted from ref. [55]).

In modeling the use of biogas, there are also other examples. The main advantage of these solutions is the possibility of using them in regions that are economically less developed. There are a couple of alternatives to this. The first solution considers the microturbine as the primary drive, and the second considers the internal combustion engine. Both are combined with an absorption cooling system and a bio-slurry dryer. The energy source is based on the use of cattle dung for central biogas production. The final services provided to the plants are biogas, electricity, refrigeration (for preserving milk), and fertilizers [78]. The refrigeration alternative is relatively less used, but its adoption can increase a wide range of synergies in biogas production. In any case, the palette of final products is completed by biological fertilizers, which are applied for a new crop. According to the results of the aforementioned study, the polygeneration plant which implies the use of an internal combustion engine was found to be the most promising option as it has the lowest economic cost, was electricity efficient, and needs little support to compete in the market [79]. Economies of scale are an important factor in the biogas production business. Farms planning to make investment decisions must clearly assess the possibilities of developing the project profitably. In this case, a problem is encountered as not all farms have clear operational or development plans, so the development of the biogas project may be of poor quality. Larger farms have more opportunities to profitably develop energy production activities. The analysis has shown there are relatively high initial investment costs, especially for small biogas installations. The smaller the installation, the higher the investment cost per unit of capacity [80]. For small farms, it is necessary to work cooperatively and for this it requires a lot of attention from the state [81,82]. Otherwise, there is a risk of preserving sources of pollution that would be associated with small- and medium-sized farms. The state can help these farms in two ways. In the first case, subsidies may be provided for the energy sold. This is no longer an acceptable option due to cheaper renewable energy technologies. Another alternative is the procedure for issuing a simplified and prioritized construction permit for the biogas power plant. This would reduce the initial costs of small farms or their cooperatives and accelerate energy transformation in the agricultural sector.

The use of biogas promotes the growth of farm income in several directions. First, the manure generated on the farm later enters the fields without gas, which is concentrated in biogas reactors. Depending on the level of infrastructure, electricity, heat, or biomethane is produced from the gas. The calculations presented in Table 5 show that a farm that has chosen the electricity/heat or biomethane production mode can expect a stable operating income. The main environmental benefit is the prevented release of methane into the environment, which is released by rotting cow manure. A farm operating a typical 1 MW power plant can diversify farm risks while also creating additional sources of income. Such a reactor is suitable for larger farms and agricultural cooperatives

Table 5. Environmental and economic benefits from 1 MW power biogas plant in farms [83–86].

Regime	Production, MWh	Average Price, EUR/MWh	Incomes, EUR	Environmental Impact
Electricity production,	8400	50	420,000	Methane emission reduction approx. 20 times.
Heat production *	8900	15	133,500	
Biomethane production	10,000	90	900,000	

*—in case the farm has a connection to the grids.

The increased focus on biomethane production in Europe reflects the region's broader strategy for transitioning to a more sustainable and resilient energy system. This shift not only supports environmental goals but also creates local workplaces and promotes energy independence by reducing reliance on imported fossil fuels. In the case of agriculture, it is necessary to develop clear operating principles that will allow a smooth transition to the energy production sector using the bio-waste generated. Clear models that focus on exploiting synergies between agriculture and energy for decarbonization can help achieve this objective.

4. Agriculture and Energy Sector Synergies Model

When modeling changes in the energy system in the case of agriculture, it is assumed that biogas is the main axis of change. Due to the best use of synergistic effects and the possible stable production, biogas technology is suitable for farms. However, it is necessary to emphasize that other types of energy production also meet the development goals of farms and can be integrated into the existing farm infrastructure.

The benefits of biogas development would have the greatest impact on climate change mitigation in agriculture. Different energy production solutions can be combined on the basis of biogas. If biogas is used to produce biomethane, the power plant can use solar or wind energy. When using these types of energy, it is recommended to combine them with energy storage solutions. The use of solar energy is fully compatible with the principles of sustainable development. If the gaps between the solar modules are large, there is a possibility of extracting production from the land areas (grass, berries, etc.) [87,88]. If the gaps are smaller, this area of land is suitable for small animal husbandry [89]. Raising animals such as sheep or goats is beneficial due to the possibility of producing higher value-added products, while providing the animals with the opportunity to eat grass and shelter from the sun [90]. Some farms that will only develop solar energy may have to partially change the way they farm by starting to raise other types of animals. Co-land for agriculture and PV agrivoltaics is an increasingly popular alternative to solar energy production. This intentional integration of agriculture and PV is aimed at reducing competition for land use and to increase the income of the landowners along with other benefits [13]. Solar energy can reduce the costs for a farm's electricity and heating. Solar energy collected can be used to dry crops and heat homes and stables. Solar water heaters can provide hot water for running using daily and cleaning houses. Photovoltaics (solar panels) can power agricultural operations, remote water pumps, lighting, and electric fences. Rooms and barns can be set up to capture natural daylight, and instead of using electric lamps. Solar power is generally less expensive than main power lines, making the farm more cost-effective [91]. Thus, solar energy in agriculture can solve the problems associated with increasing population and limited land by increasing the economic returns of farmers and environmental agriculture, demonstrating a controlled enhancement to improve the environment by reducing CO_2 emissions [92]. In the case of wind farms, crop production can be carried out essentially without restrictions. If power plants and access roads are designed compactly, this takes up a relatively small area of cultivated land [93]. However, modern wind power plants can meet not only the needs of the farm, but also wider ones. Surplus energy can be realized in the market, especially at this moment when there are no developed cost-effective and efficient energy storage technologies like batteries. The construction of the wind power plant can be carried out independently, with partners (potential energy users), or by operating in a cooperative of farmers. However, on-farm wind energy initiatives are still quite rare. Due to huge investments in wind, policymakers and investors are continuously developing new ways to narrow the cost–benefit gap. Today, the importance of wind in agriculture has decreased [94]. In addition to the already mentioned technologies, there are opportunities to develop combined wind and solar energy activities. For this, a certain area of land would have to be donated, where only energy activities or small animal husbandry would be developed. However, western Europe faces an ethical dilemma—how to enable farmers to participate in the energy sector in the interests of society [95–97]. The main interest of the public is the possibility of self-sufficiency in locally produced food at a competitive price. Unmeasured expansion of solar and wind farms on farmer-owned land can occur when large investment funds, state-owned companies, or entrepreneurs invest in it. In this case, it is necessary to ensure that it will be possible to engage in animal husbandry activities in these areas. However, growing grain in areas with abundant solar cells is no longer possible. In order to ensure the interests of decarbonization in agriculture and the strengthening of farms, it is necessary to establish clear conditions when solar energy can be developed industrially. This may involve the use of less productive or abandoned land from which it would be difficult to obtain a competitive economic result.

There are constraints to achieving a positive effect from farm activities. Often these are financial or economic in nature. There are a limited number of farms that can develop energy activities on their own. In other cases, financial or administrative resources may not be sufficient. However, project management has a major impact in all cases, regardless of the size of the farm. The main challenges for the deployment of renewable energy systems on farms relate to the integration of such systems into the farm structure. Synchronization of production and consumption processes is essential for the use of energy produced on the farm [98]. This will entail additional costs for farmers. There may also be infrastructure barriers. As the development of renewable energy involves partial decentralization of the grid and ensuring smart grid management may pose challenges, at least in the short term [99]. Institutional and social interactions to involve local communities and farmers are important here [100]. In an effort to reduce farmers' skepticism about energy sector development, the involvement and encouragement of the government and municipalities will shape a substantial impact. Financial support does not constitute a major influence, but rather administrative assistance in obtaining permits and preparing business plans [101]. When introducing new technologies in the agriculture sector, it makes sense to target those on lower incomes. This is being performed in developing countries in order to reduce regional exclusion. It would make sense to apply this model to the rest of the world [102]. In general, the absence of a long-term and clear policy on the deployment of RES deprives countries of the opportunity to a achieve competitive advantage. It is not enough to just develop infrastructure. Instead, there is a demand to also balance consumption, have a clear roadmap for development, and promote regional initiative [103]. Farmers can make a significant contribution to a country's energy goals, but it is necessary to have a clear framework for how this initiative will be developed.

Figure 4 presents a typical energy development framework for a medium or large farm unit. It can also be applied to small farm cooperatives. The model emphasizes the energy products created and the possibilities of cooperation with external entities. It is necessary to emphasize the fact that to avoid the use of food waste, cooperation between farmers and local communities is necessary. The latter can supply biogas reactors with food waste from schools, public catering facilities, etc. This would make it possible to comprehensively solve the problems of managing both food waste and organic waste generated on farms [104]. The directions of energy consumption are chosen considering the activities that can be developed in the farms and their energy needs. A particularly important factor is the possibility of using the heat generated in biogas reactors for grain drying. This is still a rarely used solution, but it allows us to immediately replace diesel fuel or coal, which is usually used for such cases [105]. If the biogas power plant is built closer to the source of heat consumption, it can be realized on the market [106]. The scheme also assesses potential synergies between different types of renewable energy, thereby complementing the farm's energy system. The main principle of drawing up the scheme is profitability. The aim is for farmers to use technologies that have real payback. The impact on the environment is also assessed, with the aim being for minimal interventions, essentially without changing the relief and landscape of the area. Primary preference is given to energy consumption inside the farm, selling excess energy. If there is no such possibility, biomethane production on the farm and its delivery to centralized biomethane injection points are evaluated. On the right side of the picture, the activity of using the obtained organic fuel is marked. They directly reduce the need for fossil fuels both in the farms and in the market.

The model is based on the use of synergy. They are formed both in energy production and in energy consumption goals. The greatest areas of synergy are related to electricity production. If a farm has, say, solar and biogas capacity, it can have balanced energy production. During the day, solar energy can be used, while at night or during cold weather, the electricity produced in the biogas reactor would be used in time. The farm manages the main resources needed for energy—land (solar and wind energy), as well as biological waste (biogas power plant). Conditions for cooperation emerge from both sides. In the case of waste utilization, it can be delivered to the biogas reactor not only by the farmer or members of the cooperative, but also by local communities. In the case of land, agriculture can develop power plants independently or accept business partners. According to this scheme, the benefits of biogas development for the farm are the greatest.

By consistently investing in biogas extraction and utilization capacities, the farm will not only be able to develop decarbonized activities but also become more financially stable. The model assesses the situation when the surplus energy produced on the farm can be sold on the market, thereby generating additional income.

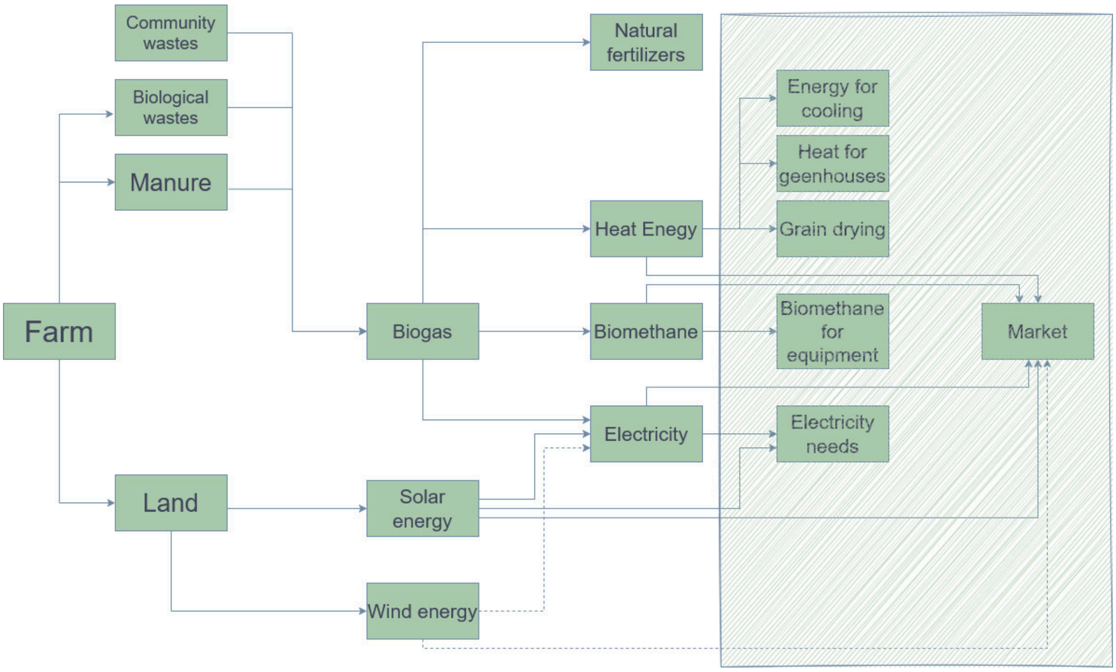

Figure 4. A framework for mitigating the consequences of the agricultural sector's contribution to energy sector change.

In the near future, it will be necessary to evaluate not only the decarbonization of farms in terms of energy resources, but also the reduction in pollution in daily farm processes. It will be possible to achieve this by creating fodder, the digestion of which emits less pollution, by improving no-till technologies, but the most important factor is the reduction in the use of mineral fertilizers and chemical products. In the latter case, products of biological origin are already distributed on the market, which can replace some chemical products. They are associated with better absorption of minerals from the soil. Meanwhile, in the case of fertilizers, the substances formed in biogas plants will have a significant influence. These aspects also have synergy with the daily activities of the farm. This allows us to say that farming activities in the future will have particularly serious challenges in the decarbonization process, since all the main elements of farm activities are in one way or another related to pollution. This leads to the need to invest in technologies suitable for farms as failure to do so may lead to the risk of the agricultural sector becoming one of the most polluting sectors in the long run. This requires the concentration of the state, private business, technology developers, venture capital funds and, of course, farmers. The slow development of new technologies increases the payback period of investments and may make farms less competitive in the future. Moreover, external assistance is necessary because in the future advanced farms investing from their own funds may be outcompeted by farms located in continents other than Europe, North America, or Australia, which have more liberal pollution regimes and lower levels of control. These programs present challenges that, if left unchecked, could mean even greater ecological, social, and economic problems both regionally and nationally.

The waste generated in the farms, available land areas, and consumption points, open opportunities to decarbonize this sector. Due to the lack of adapted technology, suitable for the agricultural sector, decarbonization may be slower than in other sectors. However, agriculture can contribute to a positive breakthrough in the energy sector by realizing surplus energy produced on farms. To achieve positive results, it is necessary to enable farms, especially medium-sized ones, to engage in this activity by giving them priority when connecting to networks and encouraging the recycling of community waste.

5. Conclusions

The decarbonization potential of the agricultural sector in the world is not yet fully exploited. This is especially true when it comes to the development of new technologies, monitoring the ecological footprint. What is more, the public is still not fully aware that the decarbonization of the agricultural sector is necessary for the success of mitigating the global climate collapse. This creates the need to invest in solutions to achieve decarbonization goals. The agricultural sector plays an important role in this process [102]. The solutions proposed in this article orient the farms towards the pursuit of synergies, thereby obtaining a positive both ecological and financial impact. Synergistic effects will help save farmers' resources and implement investment projects faster. The main axis of investment proposed in the article is the development of biogas power plants to produce heat, electricity, or biomethane (when the gas is cleaned and supplied to gas transmission network). With this technology, wind and solar power plants can be combined, the development of which have the least impact on the environment. The development of biogas power plants complies with the principles of a circular economy and sustainable development, thus enabling the farm to provide itself with energy by utilizing waste.

When applying energy transformation activities in agriculture, it is necessary to take into account environmental interests. Manure is a particularly important fertilizer, which is why its processing into biogas takes away the opportunity to carry out important agricultural processes such as the maintenance and cultivation of humus and positive soil biodiversity. When making a decision to process manure in biogas reactors, it is necessary to diversify the range of plants grown on the farm. It is especially important to use catch crops, which will help maintain a good agronomic condition of the soil. The development of biogas energy must be balanced, which is ensured by constant monitoring of the soil condition. In the case of negative deviations, the benefits created by biogas production will be less than the damage caused by soil degradation.

The main challenges for energy consumption in the future are related to the growing use of electric vehicles and the expanding possibilities to generate heat or cooling in households using electricity. All this will stimulate further exploration of synergies between different technologies as well as energy saving and efficiency initiatives. With consumption in other areas remaining broadly unchanged, further strong growth in the electricity generation sector is expected. Synergies between the energy sector and agriculture will become increasingly important to meet environmental challenges. Decarbonization of the agricultural sector uses local waste or land, thus supporting the principles of sustainable development.

Main policy implications are as follows:

1. To create conditions for farms to develop investment projects in order of priority, reducing bureaucratic obstacles must be done (especially in the areas of power plant design and connection to networks). This is linked to a clear contribution from the state in creating incentive models that will accelerate the development of on-farm renewable energy solutions. The political initiative is particularly important in this case, as farmers are faced with a lack of information and a fear of expanding their economic activities. This could include easier access to building permits, and more liberal sanitary zones for those farms with gas collection equipment.

2. Quantitatively promoting the cooperation of small- and medium-sized farms, providing the opportunity to receive support for jointly managed biogas power plants. In this case, the State's contribution is crucial: by quantitatively stimulating cooperation, new cooperatives will be established more quickly, thus automatically accelerating new economic activity. The development of regional cooperatives avoids the situation where large national or cross-border projects are delayed by excessive bureaucracy. Simplifying the red tape involved in setting up cooperatives and providing financial incentives for their development would help to decarbonize the agricultural sector more quickly, especially small- and medium-sized farms.
3. To help create short bio-waste supply chains between the community and the local biogas plant.
4. To encourage farms to use the energy they have produced primarily inside the farm, and to sell the surplus on the market.

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