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Techno-Economic Assessment of Anaerobic Digestion Technology for Small- and Medium-Sized Animal Husbandry Enterprises

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Abstract: Investments in small and medium-sized anaerobic digestion facilities have the potential to boost biogas production in Greece and other EU countries. This study aimed to evaluate the economic feasibility of anaerobic digestion facilities equipped with combined heat and power (CHP) units ranging from 50 to 400 kW, while treating livestock waste. For this purpose, data were gathered from various livestock operations (dairy cattle, poultry, swine, dairy sheep and goats) regarding their annual production, revenues, electricity and fuel usage, and waste generation. Waste samples were then collected and analyzed to assess their biochemical methane production potential. The capital and operational costs of anaerobic digestion facilities, from 50 and 400 kW, were calculated using the equations developed within the “eMT cluster” project. Findings indicate that current feed-in tariffs (FITs) of 0.21 € kWh⁻¹ are insufficient to incentivize investment in anaerobic digestion facilities with capacities below 250 kW, highlighting the need for increased FIT rates or capital expenditure subsidies. Recommendations include shifting towards simplified technology and business models with reduced farmer involvement, coupled with supportive legislative framework and long-term electricity price guarantees. These measures are expected to foster the implementation of anaerobic digestion projects in the animal husbandry sector.

Keywords: anaerobic digestion; biogas; circular economy; manure; sustainable production; waste management; cost equations

1. Introduction

Historically, the management and disposal of manures from small and dispersed livestock farms was not considered a problem [1]. Besides, these wastes, both solid and liquid, were rich in organic matter and nutrients, primarily nitrogen, phosphorus, and potassium, making them valuable for maintaining soil fertility [1,2]. Until now, they are typically spread on arable land after undergoing long-term stabilization in lagoons and composting piles [3]. Unfortunately, in such cases, the energy content of manure is not utilized, combined with the release of greenhouse gases, notably methane, and odors into the atmosphere [4]. Incidents of surface and groundwater pollution are frequently reported when lagoons and composting pits lack proper insulation [5]. Nowadays, the importance of sustainable livestock waste management, environmental protection, and creating value for farmers is increasingly recognized.

Energy recovery from animal waste can be achieved through thermal or biochemical processes [6,7]. One widely used technology for livestock waste treatment is anaerobic digestion, a biochemical process wherein organic compounds are converted into biogas
Biogas typically comprises methane (55–65%), carbon dioxide (45–35%) and traces of other gases, like sulfide and ammonia [8]. The residue left after anaerobic digestion, known as digestate, is rich in organics and nutrients and can serve as a soil conditioner to enhance agricultural production [9]. Implementing anaerobic digestion technology offers several advantages, including waste volume reduction, odor control, decrease in manure pathogens (especially during thermophilic processes), recovery of nutrients in digestate, and energy production [10].

Anaerobic digestion facilities represent complex technical systems that demand substantial investments in infrastructure, such as buildings and tanks, mechanical and safety equipment [11,12]. The setup of such a facility involves meticulous design, construction of infrastructure, acquisition and installation of equipment, operation overseen by trained personnel, and annual maintenance to minimize or address unforeseen breakdowns. Specialized construction firms, known as EPC technology providers, collaborate with waste producers (i.e., livestock farmers) to establish these facilities. Given the variations in livestock farms regarding type and size, leading to the generation of diverse types and quantities of waste, technology providers implement customized solutions tailored to each client’s needs. These solutions encompass various aspects, including anaerobic digestion technology (e.g., wet, dry, mesophilic, thermophilic) and waste pretreatment technology, as well as equipment for biogas utilization (e.g., hot water production, electricity, and heat, or biomethane upgrading).

According to the European Biogas Association (EBA), as of 2023, Europe hosted ~21,000 anaerobic digestion facilities generating approximately 21 billion cubic meters (bcm) of biogas. While biogas was primarily utilized for electricity generation, there was a growing trend of upgrading it to biomethane, which was either injected into the natural gas grid or used as a vehicle fuel. The EBA reported a significant increase in biomethane production from 0.9 to 4.2 bcm between 2013 and 2023. Despite this progress, the Repower EU initiative has set a target of further increasing biomethane production to 35 bcm by 2030. Achieving this objective necessitates the establishment of an additional 14 bcm of biogas production capacity, equivalent to the construction of ~14,000 new anaerobic digestion facilities, alongside the conversion of existing facilities into biomethane plants. Many European countries, such as Greece, Ukraine, Latvia, Ireland and Serbia, lag behind in biogas production, each hosting fewer than 60 biogas plants. Consequently, a considerable amount of energy from manure remains untapped. The advantages of expanding anaerobic digestion facilities are manifold and include bolstering the local economy, generating new job opportunities (both during construction and operation), safeguarding the environment and public health, reducing greenhouse gas emissions, and enhancing the production of renewable fuels [13–16].

Implementing anaerobic digestion for waste management in small and medium-sized animal husbandry operations presents significant challenges. Moreover, the EU agro-food sector is characterized by a multitude of small and medium-sized enterprises [17]. In such scenarios, the expenses associated with collecting and transporting waste to large centralized anaerobic digestion facilities are substantial, ranging from 0.15 to 0.20 € tn⁻¹ km⁻¹ [18]. For instance, for a 500-kW anaerobic digestion facility processing 30,000 tn of livestock and/or agro-industrial waste annually, transportation costs could amount to as much as 120,000 € per year [19]. Additionally, plant operators often resort to energy crops to enhance biogas production, a practice that can potentially double operational expenditures, considering the utilization of 2000 tn of maize silage per year, with prices ranging between 40 and 60 € tn⁻¹ [19].

Small-size anaerobic digestion facilities designed for individual farms do not necessitate additional raw materials or the use of energy crops. Consequently, operating costs are primarily limited to electricity consumption (for mechanical equipment), labor salaries, equipment maintenance (including CHP unit, motors and pumps), the use of chemicals (e.g., for biogas desulfurization), and consulting services. These consulting services
typically offer specialized expertise to optimize digester operation and may also provide chemical additives aimed at enhancing biogas production efficiency.

This study aimed to assess the economic feasibility of small-size anaerobic digestion facilities equipped with combined heat and power (CHP) engines ranging from 50 to 400 kW, for treating livestock waste from individual animal husbandry enterprises. To achieve this goal, data were gathered from various livestock operations (including dairy cattle, poultry, swine, dairy sheep and goats) regarding their annual production, revenues, electricity and fuel usage, as well as waste generation. Additionally, waste samples were collected and analyzed to determine their biomethane production potential, thus estimating the revenue from renewable electricity generation. The capital and operational costs of anaerobic digestion facilities, ranging from 50 and 400 kW in capacity, were calculated using the equations developed within the “eMT cluster” project. The economic feasibility was further evaluated by computing the investment payback period, considering different feed-in-tariffs for electricity fed into the grid (ranging from 0.21 to 0.26 € kWh\(^{-1}\)), as well as potential subsidies for the construction of anaerobic digestion plants.

2. Materials and Methods

2.1. Inventory on Animal-Husbandry Enterprises

To gather data on the operations of various animal husbandry enterprises, interviews were conducted with the owners or managers of these facilities [20]. The interviews addressed several aspects of the production process, including:

- Herd size;
- Type of products and annual production volumes;
- Prices of products;
- Annual quantity of animal feed;
- Annual quantity of waste generated;
- Annual electricity consumption;
- Annual consumption of fossil fuels.

The data were normalized per tn of product to facilitate comparison across different sectors. Electricity and fuel prices were based on the average market values in Greece, which were 0.10 € kWh\(^{-1}\) for electricity and 1 € kg\(^{-1}\) for LPG or diesel oil. The carbon dioxide footprint was calculated using emissions factors of 0.34 kg CO\(_2\)eq per kWh of electricity and 2.0 kg CO\(_2\)eq per kg of fuel [21].

2.2. Waste Sampling and Characterization

To assess the biochemical methane potential (BMP) of organic wastes, samples were collected from various animal husbandry enterprises and analyzed for their physical and chemical properties. The waste samples were stored in plastic containers at 4 °C until processing. The waste characterization involved determining the total solids (TS) and volatile solids (VS) content using standard methods [22]. BMP tests were conducted in anaerobic batch digesters with a working volume of 250 mL, placed inside an incubator (WITEG, Wertheim, Germany) under mesophilic conditions (38 °C). The digesters were inoculated with anaerobic sludge from an agricultural digester for treating manure and energy crops. The substrate-to-inoculum ratio was kept constant at 0.25 kg VS substrate per kg VS inoculum. During batch anaerobic digestion, mixing was applied manually once per day. Biogas production was monitored daily over a 20-day period using an inverse water column with acidic water (pH = 2), and the methane content of the biogas was determined using an alkaline trap [23]. BMP was calculated as the cumulative methane production per gram of VS added, converted to standard temperature and pressure conditions.

2.3. Anaerobic Digester Techno-Economic Assessment

The techno-economic assessment of anaerobic digestion facilities, ranging from 50 to 400 kW installed CHP electric power, entailed both capital (CAPEX) and operational
(OPEX) expenditures. CAPEX included the engineering, procurement, and construction of various components, such as a buffer tank with a mixer and pumps, a digester tank with a mixer, heat exchanger, and a membrane gas holder [24–26]. Additionally, biogas equipment comprising a scrubber, dryer, and combined heat and power (CHP) unit was accounted for, along with monitoring equipment including liquid and gas flow meters, temperature, pressure, and level sensors. Safety equipment, such as flare, pressure relief valves, flame arresters, and explosivity sensors, were also included in the CAPEX assessment. CAPEX was determined using Equation (1):

\[
\text{CAPEX} = V_{DG} \times [1000 - 40 \times \ln(V_{DG})],
\]

where, \( V_{DG} \) is the digester working volume (m\(^3\)). The latter was determined using the following equation:

\[
V_{DG} = 24 \times Q_{W} \times VS / OLR,
\]

where \( Q_{W} \) = waste mass flow rate (tn h\(^{-1}\)), \( VS \) = waste volatile solids content (kg tn\(^{-1}\)), and \( OLR \) = design organic loading rate (considered equal to 4 kg VS m\(^{-3}\) d\(^{-1}\), typical for CSTR digesters [19]). Finally, CAPEX was converted to equivalent annual CAPEX (CAPEXan) considering a 15-year life-time period and 6% interest [18].

The annual operational expenditures (OPEX) encompass expenses related to electricity (for operating mixer, pumps, CHP unit, etc.), equipment maintenance (for CHP unit, pumps, motors, etc.), labor, and consulting services. The installed electric power (P in kW) of the anaerobic digestion facility’s production equipment was determined using the following equation:

\[
P = V_{DG} \times [0.082 - 0.008 \times \ln(V_{DG})],
\]

Thus, the annual electricity expenditures (E, in € yr\(^{-1}\)) were determined as follows:

\[
E = P \times WP \times EC,
\]

where \( WP \) = the annual working hours of electrical equipment (considered equal to 8000 h), and \( EC \) = the cost for electricity (considered 0.10 € kWh\(^{-1}\)). The annual costs for maintenance (M, in € yr\(^{-1}\)), labor (L, in € yr\(^{-1}\)) and consulting services (C, in € yr\(^{-1}\)) were calculated using Equations (5)–(7):

\[
M = 27.5 \times V_{DG} - 0.0046 \times (V_{DG})^2,
\]

\[
L = 10,000 \times \ln(V_{DG}) - 50,000,
\]

\[
C = 1800 \times \ln(V_{DG}) - 5300,
\]

The total cost, total income (from electricity introduction into the grid) and total profit (before taxes) were determined using Equations (8)–(10):

\[
\text{Total cost} = \text{CAPEXan} + E + M + L + C,
\]

\[
\text{Total income} = Q_{W} \times VS \times BMP \times WP \times \text{CHPeff} \times \text{FIT},
\]

\[
\text{Total profit} = \text{Total income} - \text{Total cost},
\]

where CHP\(_{eff}\) = the efficiency of the CHP (range from 3.6 to 4.1 kWh-el m\(^{-3}\) CH\(_4\)), and FIT = the feed-in tariff for electricity introduction to the grid (considered equal to 0.21 € kWh\(^{-1}\)). The investment payback period (in years) was finally determined using Equation (11):

\[
\text{Investment payback period} = \text{Total profit}/\text{CAPEX},
\]
3. Results

3.1. Waste Characteristics and Biochemical Methane Potential

Wastes generated by various animal husbandry enterprises were either liquid (from dairy cows and swine) or solid (from poultry, dairy sheep, and goats). Table 1 provides a summary of their characteristics and biochemical methane potential. Poultry and dairy cattle wastes exhibited the highest BMP values, followed by sheep and goat manure. Swine manure, on the other hand, showed low BMP values along with a high-water content. As evidenced by the data provided in Figure 1, the methane production from the examined substrates was completed within 20 d of anaerobic digestion time. The methane content in biogas was on average 62 ± 3% in all samples tested.

Table 1. Concentration of total solids (TS), volatile solids (VS) and biochemical methane potential (BMP) values for waste samples collected from different animal husbandry enterprises.

<table>
<thead>
<tr>
<th>Waste</th>
<th>TS (g kg(^{-1}))</th>
<th>VS (g kg(^{-1}))</th>
<th>VS/TS</th>
<th>BMP (mL CH(_4) g(^{-1}) VS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy cattle</td>
<td>83.1 ± 4.6</td>
<td>70.1 ± 4.1</td>
<td>0.84</td>
<td>276 ± 3</td>
</tr>
<tr>
<td>Poultry</td>
<td>692.5 ± 4.1</td>
<td>554.6 ± 6.5</td>
<td>0.80</td>
<td>320 ± 19</td>
</tr>
<tr>
<td>Swine</td>
<td>22.3 ± 2.5</td>
<td>15.1 ± 3.5</td>
<td>0.68</td>
<td>172 ± 2</td>
</tr>
<tr>
<td>Sheep</td>
<td>352.2 ± 14.4</td>
<td>236.3 ± 8.9</td>
<td>0.67</td>
<td>252 ± 6</td>
</tr>
<tr>
<td>Goats</td>
<td>717.0 ± 3.4</td>
<td>606.0 ± 22.4</td>
<td>0.85</td>
<td>227 ± 9</td>
</tr>
</tbody>
</table>

Figure 1. Cumulative methane production curves from the batch anaerobic digestion of different livestock wastes samples.

3.2. Techno-Economic Evaluation

According to Equation (1), the CAPEX of the anaerobic digester decreased from 6000 to 4500 € kW\(^{-1}\) (or from 800 to 700 € m\(^{-3}\)) as the plant capacity increased from 50 to 400 kW, reflecting economies of scale (Figure 2a). Similarly, operational expenses decreased from 700 to 350 € kW\(^{-1}\) with increasing plant capacity. Electricity and maintenance each accounted for 32% of the total OPEX, followed by labor (26%) and consulting services (10%) (Figure 2b).
Figure 2. (a) Capital expenses (CAPEX) in € per kW installed CHP electric power, and (b) operational expenses (OPEX) per kW installed CHP electric power, for small-size anaerobic digestion facilities, as a function of the CHP installed electric power.

Considering the above, it was possible to calculate the costs per m³ of biogas (methane) produced and per kWh of electricity generated (see Figure 3). The data indicate that the cost of biogas (methane) production decreased from 0.55 to 0.35 € m⁻³ CH₄ and the cost of generating electricity decreased from 0.16 to 0.10 € kWh⁻¹, as the digester capacity increased from 50 to 400 kW. These values fall within the same range as natural gas and electricity prices, particularly for larger CHP installations. Therefore, low prices of natural gas and electricity represent significant barriers to the penetration of anaerobic digestion into small-sized animal husbandry enterprises. Figure 3b show the energy sustainability index (ESI) of the examined anaerobic digestion facilities, representing the ratio...
of produced to consumed electricity. The data indicate that the ESI ranged between 4 and 8. The energy consumed accounted for 26% to 13% for the anaerobic digestion facilities with installed CHP electric power capacities of 50 to 400 kW, respectively.

Figure 3. (a) Capital expenses (CAPEX), operational expenses (OPEX) and total cost (TOTAL) per m³ of methane produced and kWh⁻¹ electricity generated, and (b) energy sustainability index (ESI) and electricity consumption as a percentage of produced electrical energy, for small-size anaerobic digestion facilities, as a function of the CHP installed electric power.

Figure 4 depicts the investment payback period of anaerobic digester investments as a function of CHP installed electrical power for various scenarios of financial support. In the case of a feed-in tariff (FIT) equal to 0.21 € kWh⁻¹, the payback period decreased from 15 to 5 years as the digester capacity increased from 50 to 400 kW. Consequently, facilities below 250 kW become less attractive from an investment perspective. With an increase in the FIT to 0.26 € kWh⁻¹, the payback period for facilities under 250 kW remains between 5 and 7 years. Similar performance was observed when subsidizing 70% of the CAPEX for
construction instead of electricity FIT. If both CAPEX subsidy (70%) and high electricity prices are available, the overall payback period for the examined anaerobic digestion facilities ranges between 3 and 5 years, rendering them financially attractive.

![Figure 4. Investment payback period for anaerobic digestion facilities as a function of the CHP installed electric power, for different feed-in tariffs (FIT) and construction subsidies. The FIT was considered as 210 € MWh$^{-1}$ (FIT210) or 260 € MWh$^{-1}$ (FIT260) and the construction subsidy equal to 70% of the CAPEX (CAPEX70).](image)

3.3. Livestock Enterprise Inventory and Anaerobic Digester Economic Feasibility Assessment

Electricity consumption and fossil fuel usage are seldom major concerns for farmers. In addition, the costs associated with electricity and fuel consumption represented less than 3 and 5% of the annual turnover, respectively (see Table 2). Dairy cattle farming exhibited high electricity consumption per tn of product, while poultry farming showed high fuel consumption, followed by dairy cattle. However, with the rise in electricity and fossil fuel prices, as witnessed during 2022–2023 in Europe, their respective contributions may significantly increase.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dairy Cattle</th>
<th>Poultry</th>
<th>Swine</th>
<th>Sheep/Goats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herd size</td>
<td>680</td>
<td>4,120,000</td>
<td>5,550</td>
<td>2,000</td>
</tr>
<tr>
<td>Product type</td>
<td>Milk</td>
<td>Meat $^a$</td>
<td>Meat $^a$</td>
<td>Milk</td>
</tr>
<tr>
<td>Price ($€$ tn$^{-1}$)</td>
<td>400–500</td>
<td>1,500–2,500</td>
<td>1,200–1,600</td>
<td>1,200–1,600</td>
</tr>
<tr>
<td>Production (tn yr$^{-1}$)</td>
<td>2,740</td>
<td>1,200 $^a$</td>
<td>1,280 $^a$</td>
<td>200</td>
</tr>
<tr>
<td>Feed (tn yr$^{-1}$)</td>
<td>5,300</td>
<td>200</td>
<td>4,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Wastes $^b$ (tn tn$^{-1}$)</td>
<td>7.2</td>
<td>0.8</td>
<td>8.6</td>
<td>6.0</td>
</tr>
<tr>
<td>Electricity $^b$ (kWh tn$^{-1}$)</td>
<td>119</td>
<td>96</td>
<td>140</td>
<td>100</td>
</tr>
<tr>
<td>Fuel $^b$ (kg tn$^{-1}$)</td>
<td>13</td>
<td>83</td>
<td>9</td>
<td>20</td>
</tr>
</tbody>
</table>

$^a$ Expressed as live weight; $^b$ the price of product, the quantity of wastes generated, the quantity of electricity and fuels consumed were expressed as per tn of product.

Table 3 represents the capital and operational expenses of small-size anaerobic digestion facilities applied to the examined animal husbandry enterprises. The annual profit in all cases was calculated using a FIT of 0.26 € kWh$^{-1}$ and an 70% investment subsidy for CAPEX. The data demonstrate that a maximum profit of 18 and 22% of their annual income was observed.
turnover is possible for the dairy cattle and sheep/goat enterprises examined, respectively. This is further reduced to 4% for poultry farms while the swine enterprise does not appear eligible for a 50-kW anaerobic digestion facility and this case was not further assessed.

Table 3. Summary of techno-economic assessment for different livestock waste anaerobic digestion facilities, considering a FIT of 0.26 € kWh\(^{-1}\) and a 70% investment subsidy for CAPEX. The case of the swine enterprise was not further assessed since the capacity of the CHP required was below the range examined in the study (50 to 400 kW).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dairy Cattle</th>
<th>Poultry</th>
<th>Swine</th>
<th>Sheep/Goats</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste (tn yr(^{-1}))</td>
<td>20,000</td>
<td>960</td>
<td>11,000</td>
<td>1200</td>
</tr>
<tr>
<td>VS content (kg tn(^{-1}))</td>
<td>70</td>
<td>555</td>
<td>15</td>
<td>420</td>
</tr>
<tr>
<td>BMP (L kg(^{-1}) VS)</td>
<td>280</td>
<td>310</td>
<td>160</td>
<td>220</td>
</tr>
<tr>
<td>(\text{CH}_4) generated (m(^3) yr(^{-1}))</td>
<td>390,000</td>
<td>175,000</td>
<td>26,000</td>
<td>110,000</td>
</tr>
<tr>
<td>Electricity produced (^{a}) (kWh yr(^{-1}))</td>
<td>1,500,000</td>
<td>660,000</td>
<td>90,000</td>
<td>400,000</td>
</tr>
<tr>
<td>CHP (^{b}) (kW)</td>
<td>200</td>
<td>80</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>Annual CAPEX (€ yr(^{-1}))</td>
<td>1,000,000</td>
<td>550,000</td>
<td>--</td>
<td>300,000</td>
</tr>
<tr>
<td>Annual OPEX (€ yr(^{-1}))</td>
<td>100,000</td>
<td>55,000</td>
<td>--</td>
<td>30,000</td>
</tr>
<tr>
<td>Total cost (€ yr(^{-1}))</td>
<td>100,000</td>
<td>60,000</td>
<td>--</td>
<td>40,000</td>
</tr>
<tr>
<td>Total income (€ yr(^{-1}))</td>
<td>200,000</td>
<td>115,000</td>
<td>--</td>
<td>70,000</td>
</tr>
<tr>
<td>Total profit (€ yr(^{-1}))</td>
<td>390,000</td>
<td>170,000</td>
<td>--</td>
<td>104,000</td>
</tr>
<tr>
<td>Annual turnover (ATO)</td>
<td>260,000</td>
<td>93,000</td>
<td>--</td>
<td>55,000</td>
</tr>
<tr>
<td></td>
<td>1,200,000</td>
<td>2,400,000</td>
<td>1,800,000</td>
<td>300,000</td>
</tr>
<tr>
<td>Profit (^{c}) (% ATO)</td>
<td>22%</td>
<td>4%</td>
<td>--</td>
<td>18%</td>
</tr>
</tbody>
</table>

\(^{a}\) The electrical efficiency of the CHP engine was considered between 3.8 and 3.5 kWh m\(^{-3}\) \(\text{CH}_4\); \(^{b}\) CHP capacity was determined considering 8000 h of anaerobic digester operation per year; \(^{c}\) Profit was expressed as a percentage of the enterprise annual turnover (ATO).

4. Discussion

Organic waste management poses a significant challenge for the animal husbandry sector, which produces substantial quantities of residues and wastes, both liquid and solid, necessitating proper treatment and disposal [25]. Inadequate waste management can result in greenhouse gas emissions, environmental pollution, health hazards, and economic losses [24]. Hence, there is a pressing need for sustainable and efficient solutions to mitigate the environmental impact of waste while extracting value from it.

Anaerobic digestion is a promising technology for the valorization of organic waste, which is widely distributed across various regions. The biogas generated (mainly methane) can be utilized for multiple purposes, including electricity generation, vehicle fuel, natural gas substitution, heating, and cooking fuel [27,28]. These facilities are complex technical systems requiring meticulous design and operation. The actual biogas yield from a full-scale facility is influenced by several factors, such as digester design (e.g., hydraulic residence time, residence time distribution, mixing intensity, presence of dead volumes/flow short-circuits), the conditions inside the digester (e.g., temperature, pH, salinity, concentration of inhibitors, like ammonia and sulfides), the presence of micronutrients and trace elements, sludge activity and the accumulation of non-digestible vegetable fibers [20,29]. Properly designed and executed BMP tests can estimate the methane yield under field conditions. Additionally, operating a pilot-scale facility with continuous substrate feeding can provide valuable data on long-term process performance, inhibitor accumulation and the composition of both biogas and digestate [29].

Sustainability, in terms of technology, economics and the environment, remains an open question that requires further analysis and evaluation. New technologies, based on high-rate digestion reactors, with low capital expenditure and low technological complexity, are crucial, especially for small-scale projects. Energy sustainability, as expressed by the Energy Sustainability Index (ESI)—the ratio of electricity produced to the electricity consumed by the
technology—is of particular importance [28]. The ESI for small-scale anaerobic digestion facilities examined in this work ranged between 4 and 8 for installed CHP electric power between 50 and 400 kW, respectively. Clearly, energy sustainability is crucial, as a technology with low ESI (even below 1) can still be financially attractive due to incentives.

Considering the economic feasibility, the findings of this study reveal that a feed-in tariff (FIT) of 0.21 € kWh$^{-1}$ is inadequate to render investment in anaerobic digestion facilities financially attractive for capacities less than 250 kW. Hence, it is imperative to either increase the FIT to 0.26 € kWh$^{-1}$ or provide investment subsidies for capital expenditures (CAPEX), or ideally, both. Investment in anaerobic digestion should yield value for the farmer, accompanied by a short payback period, preferably under 5 years. As evidenced by the results, significant economic returns are feasible for dairy cattle and sheep/goat enterprises. Poultry farms, despite their substantial consumption of fossil fuels (primarily for barn heating), incur overall fuel costs amounting to less than 5% of the annual turnover, thus mitigating the significance of this issue for farmers. Previous studies indicated that small-scale anaerobic digestion facilities are rarely implemented due to their limited financial attractiveness [30]. Nevzorova and Kutcherov [31] highlighted the barriers hindering the widespread adoption of anaerobic digestion technology in small and medium-sized livestock enterprises, including lack of interest by the farmer, high investment costs (attributed to the scarcity of qualified construction companies), limited access to bank loans, absence of suitable subsidies and support programs, and complex bureaucratic procedures for financing and obtaining permits/licenses.

According to a survey conducted by Burg et al. [32] in Switzerland, farmers with a small number of animals exhibit limited interest in biogas production. The primary motivation for adopting anaerobic digestion facilities is the potential income derived from selling electricity to the grid. Similarly, factors contributing to the limited adoption of anaerobic digestion technology include high investment costs, absence of subsidies, and difficulties in collaborating with neighboring companies to establish larger capacity plants. Furthermore, investing in anaerobic digestion technology often requires significant involvement from the farmer, spanning the design, construction, and especially operation phases, which may divert attention from their primary activities of animal breeding and/or milk production. Therefore, for the successful implementation of anaerobic digestion projects in small and medium-sized livestock enterprises, it is crucial to ensure a positive economic balance, coupled with low capital and operational expenses, while ensuring that farmers maintain their commitment to their core production activities.

5. Conclusions

Small-scale animal husbandry enterprises generally large quantities of organic wastes that require appropriate management and treatment. Anaerobic digestion facilities with capacities between 50 and 400 kW installed CHP electric power were evaluated in terms of capital and operational expenditures. Although anaerobic digestion facilities with a CHP capacity of less than 250 kW are energy sustainable, they are rarely attractive from an investment perspective. According to this study, it is possible to reduce the payback period for investing in a 100–50 kW anaerobic digestion facility from 10–15 to 6–7 years by increasing the feed-in tariff (FIT) from 0.21 to 0.26 € kWh$^{-1}$, and to 4–5 years by additionally providing financial support (a 70% subsidy) for capital expenditures (CAPEX). These recommendations are viable if electricity prices are guaranteed for the duration of the investment’s lifespan (at least 15 years) and if there is a robust legislative framework mandating the construction of anaerobic digestion facilities.

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