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Posted Date: 8 May 2024

doi: 10.20944/preprints202405.0440.v1

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

Alexandros Eftaxias [1], Iliana Kolokotroni [1], Christos Michailidis [1], Panagiotis Charitidis [2] and Vasileios Diamantis [1,2,*]

[1] Act4energy P.C., Ioannina 45333, Greece; alexeftaxias@gmail.com (A.E.); christos.michailidis1@gmail.com (C.M.); ilianako98@gmail.com (I.K.)

[2] Department of Environmental Engineering, Democritus University of Thrace, Xanthi 67132, Greece; bdiamant@env.duth.gr (V.D.); pan_har@outlook.com.gr (P.C.)

* Correspondence: bdiamant@env.duth.gr; Tel.: +30 25410 79376

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 goat) 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 (FIT) 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 and digestate. 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

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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 agroindustrial 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].

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 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 goat) 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-tarrifs 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. 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 $CO_{2\text{-eq}}$ per kWh of electricity and 2.0 kg $CO_{2\text{-eq}}$ per kg of fuel [20].

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 ^{o}C until processing. The waste characterization involved determining the total solids (TS) and volatile solids (VS) content using standard methods [21]. BMP tests were conducted in anaerobic batch digesters with a working volume of 250 mL, under mesophilic conditions (38 ^{o}C). The digesters were inoculated with anaerobic sludge from an agricultural digester treating manure and energy crops. The substrate-to-inoculum ratio was kept constant at 0.25 kg VS substrate per kg VS inoculum. Biogas production was monitored daily over a 30 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 [22]. 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. 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 the equation (1):

$$CAPEX = V_{DG}*[1000 - 40*\ln(V_{DG})], \quad (1)$$

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

$$V_{DG} = 24 * Q_W * VS / OLR, \quad (2)$$

where Q_W = waste mass flow rate (tn h^{-1}), VS = waste volatile solids content (kg tn^{-1}), OLR = design organic loading rate (considered equal to 4 kg VS m^{-3} d^{-1}, typical for CSTR digesters [19]). Finally,

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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:

$$P = V_{DG}\,[0.082 - 0.008\ \ln(V_{DG})], \quad (3)$$

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

$$E = P * WP * EC, \quad (4)$$

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 the equations (5-7):

$$M = 27.5*V_{DG} - 0.0046*(V_{DG})^2, \quad (5)$$

$$L = 10\,000*\ln(V_{DG}) - 50\,000, \quad (6)$$

$$C = 1800*\ln(V_{DG}) - 5300, \quad (7)$$

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

$$\text{Total cost} = CAPEXan + E + M + L + C, \quad (8)$$

$$\text{Total income} = Q_W * VS * BMP * WP * CHPeff * FIT, \quad (9)$$

$$\text{Total profit} = \text{Total income} - \text{Total cost}, \quad (10)$$

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 depreciation period (in years) was finally determined using equation (11):

$$\text{Depreciation period} = \text{Total profit} / CAPEX, \quad (10)$$

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 biogas production from the examined substrates was completed within 20 d of anaerobic digestion time.

Table 1. Waste characteristics and biochemical methane potential values.

Parameter	TS (g kg^{-1})	VS (g kg^{-1})	VS/TS	BMP (mL g^{-1} VS)
Dairy cattle	83.1±4.6	70.1±4.1	0.84	276±3
Poultry	692.5±4.1	554.6±6.5	0.80	320±19
Swine	22.3±2.5	15.1±3.5	0.68	172±2
Sheep	352.2±14.4	236.3±8.9	0.67	252±6
Goat	717.0±3.4	606.0±22.4	0.85	227±9

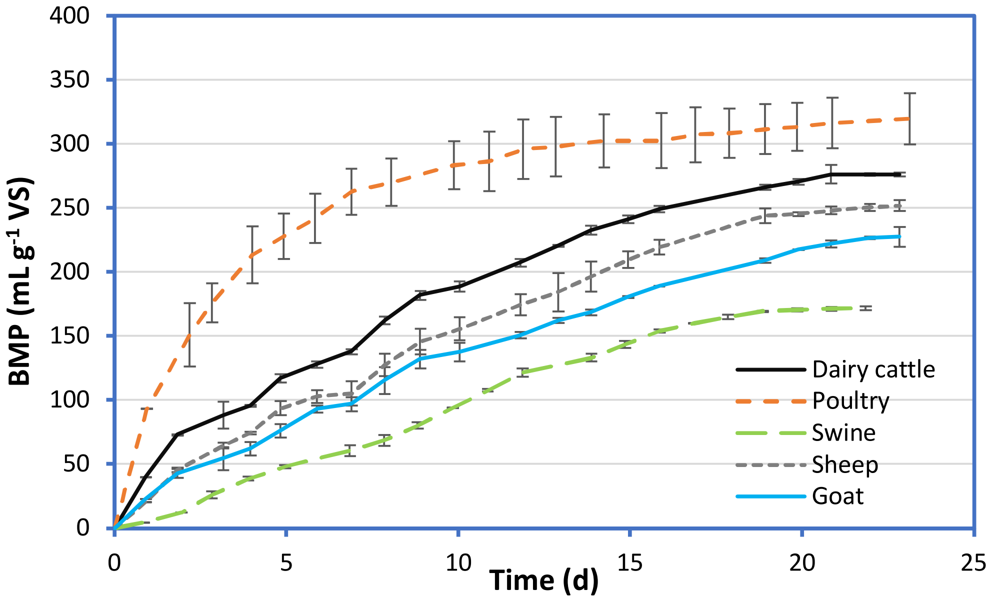
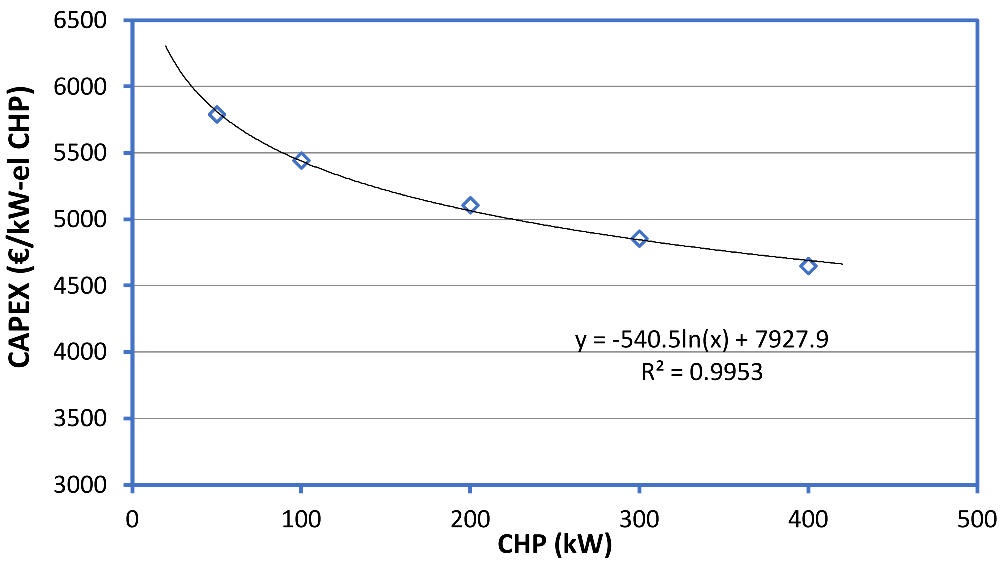


Figure 1. Biochemical methane potential values for different livestock wastes samples.

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. 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%).

(a)



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(b)

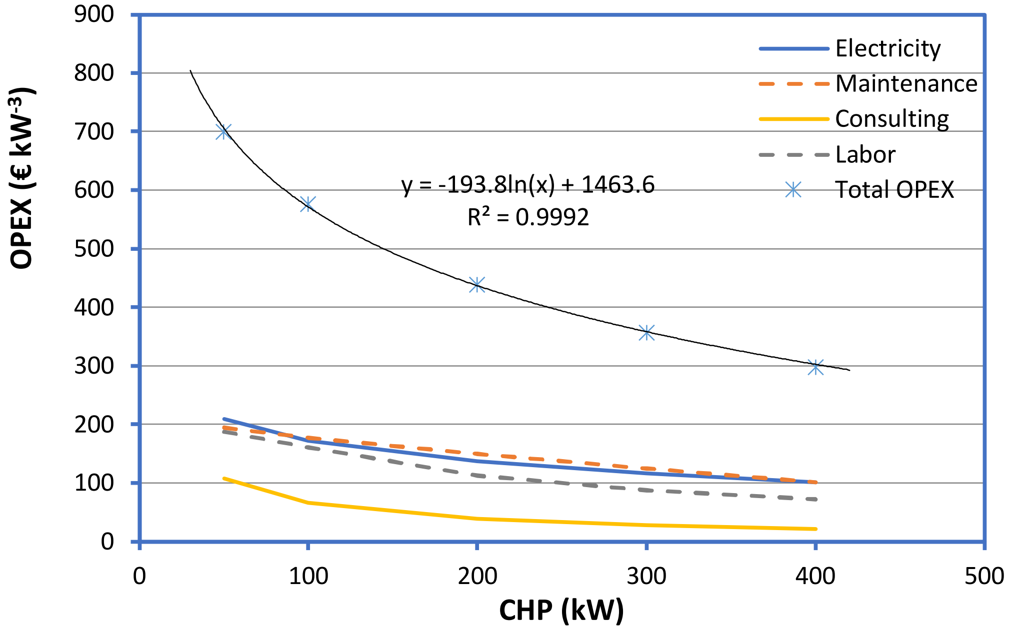
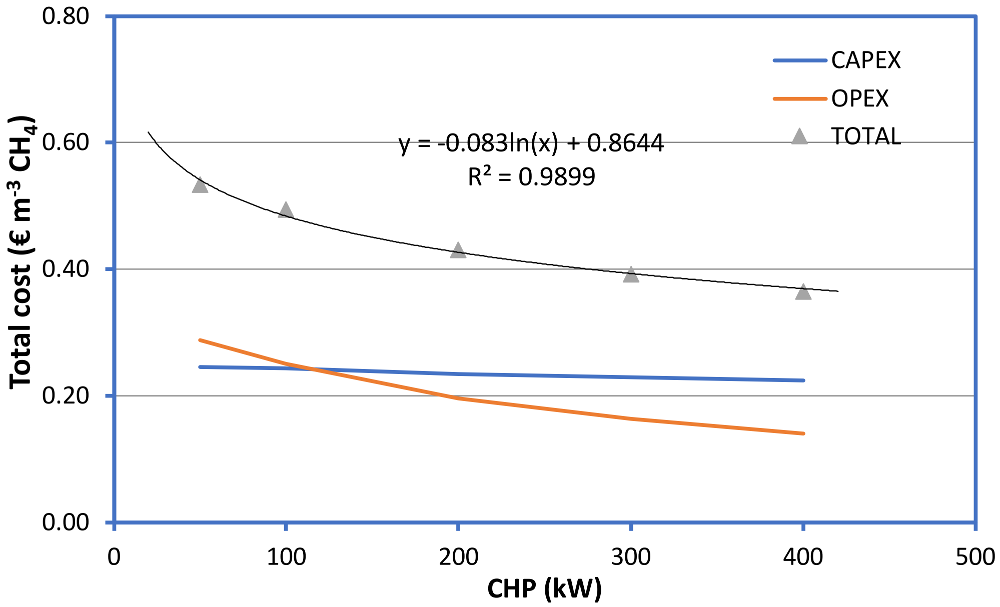


Figure 2. Anaerobic digester **(a)** specific CAPEX per kW and **(b)** specific OPEX per kW, as a function of the CHP installed electric power.

Considering the above, it was possible to calculate the costs per m^3 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 0.50 to 0.35 € m^{-3} CH_4 and the cost of generating electricity decreased from 0.17 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.

(a)



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(b)

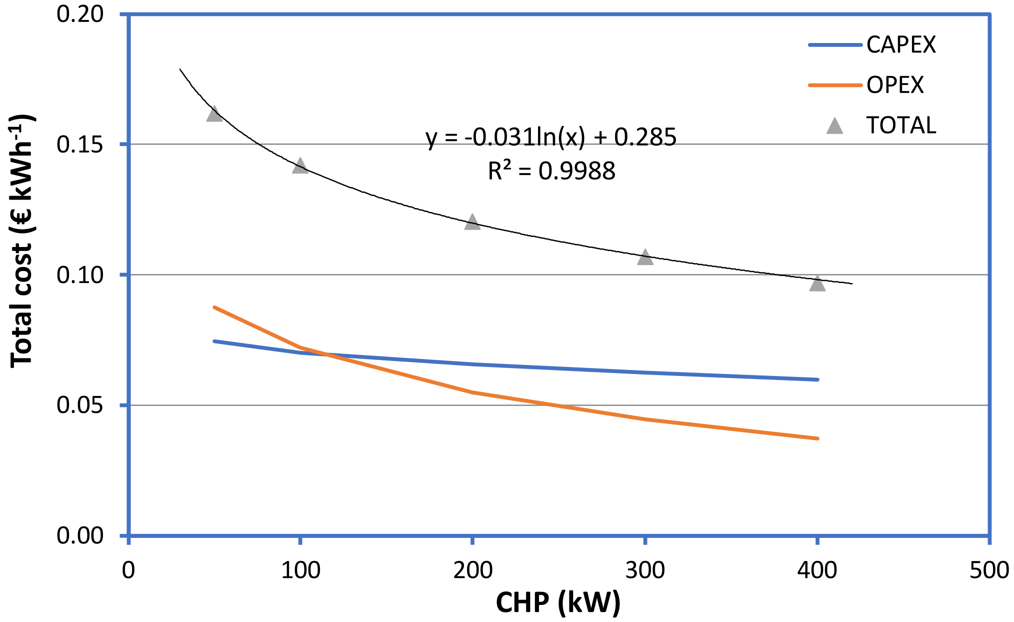

Figure 3. CAPEX, OPEX and total cost expressed as: **(a)** per m^3 methane produced; (b) per kWh^{-1} electricity generated, as a function of the CHP installed electric power.

Figure 4 depicts the depreciation 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 depreciation 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. With an increase in the FIT to 0.26 € kWh^{-1}, the depreciation period for facilities under 250 kW remain 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 depreciation period for the examined anaerobic digestion facilities ranges between 3 and 5 years, rendering them financially attractive.

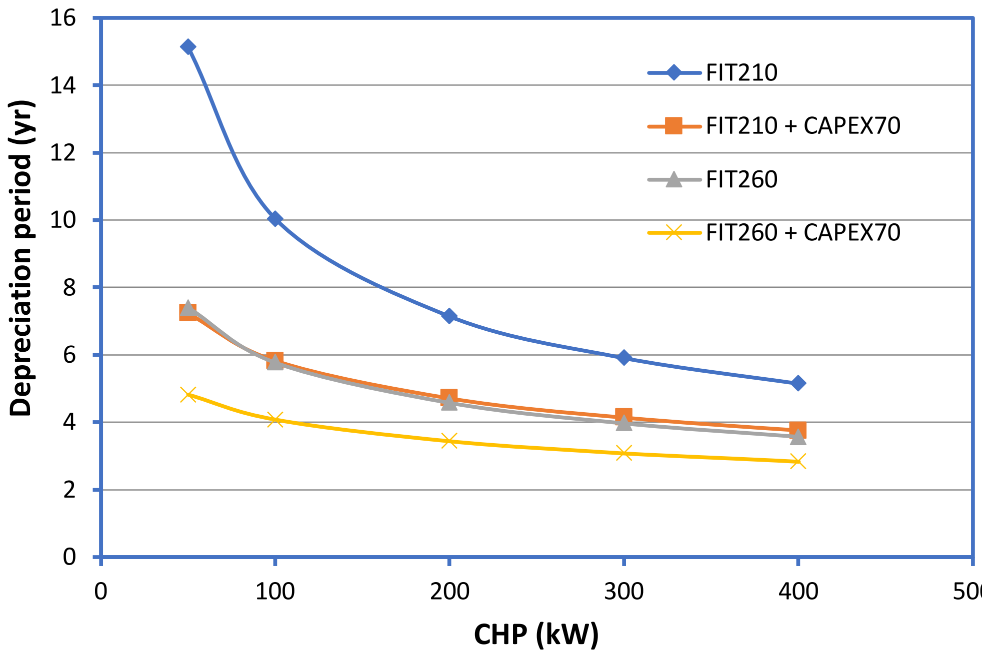

Figure 4. CAPEX, OPEX and total cost expressed as: **(a)** per m^3 methane produced; (b) per kWh^{-1} electricity generated, as a function of the CHP installed electric power.

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3.3. Livestock Enterprise Inventory

Electricity consumption and fossil fuel usage are seldom major concerns for farmers. Besides, 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 2. Inventory on operational data from different type animal husbandry enterprises in Greece.

Parameter	Dairy cattle	Poultry	Swine	Sheep/goat
Herd size	680	412 000	5 550	2 000
Product type	Milk	Meat (LW)	Meat (LW)	Milk
Price (€ tn^{-1})	400-500	1500-2500	1200-1600	1200-1600
Production (tn yr^{-1})	2 740	1 200	1 280	200
Feed (tn yr^{-1})	5 300	200	4 000	2 000
Wastes (tn tn^{-1})	7.2	0.8	8.6	6.0
Electricity (kWh tn^{-1})	119	96	140	100
Fuel (kg tn^{-1})	13	83	9	20

LW – live weight

Table 3 represents the capital and operational expenses of an anaerobic digestion facility, alongside the annual profit 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 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.

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.

Parameter	Dairy cattle	Poultry	Swine	Sheep/goat
Waste (tn yr^{-1})	20 000	960	11 000	1 200
VS content (kg tn^{-1})	70	555	15	420
BMP (L kg^{-1} VS)	280	310	160	220
CH4 (m^3 yr^{-1})	390 000	175 000	26 000	110 000
Electricity (kWh yr-1)	1 500 000	660 000	90 000	400 000
CHP kW	200	100	20	50
Digester capex	1 000 000	550 000	--	300 000
Annual CAPEX (€ yr^{-1})	100 000	55 000	--	30 000
Annual OPEX (€ yr^{-1})	100 000	60 000	--	40 000
Total cost (€ yr^{-1})	200 000	115 000	--	70 000
Total income (€ yr^{-1})	390 000	170 000	--	104 000
Total profit (€ yr^{-1})	260 000	93 000	--	55 000
Annual turnover	1 200 000	2 400 000	1 800 000	300 000
Profit (%)	22%	4%	--	18%

4. Discussion

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 financial 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 [23]. Nevzorova and Kutcherov [24] 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 [25] 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 from 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.

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. Inadequate waste management can result in greenhouse gas emissions, environmental pollution, health hazards, and economic losses. Hence, there is a pressing need for sustainable and efficient solutions to mitigate the environmental impact of waste while extracting value from it. Achieving this objective demands a paradigm shift towards a business model with minimal farmer involvement, alongside low CAPEX or simplified technology.

5. Conclusions

According to the findings of this study, the depreciation period for investing in a 50 kW anaerobic digestion facility can be reduced from 15 to 7 years, respectively, by increasing the feed-in tariff (FIT) from 0.21 to 0.26 € kWh^{-1} and to 5 years by additionally providing financial support (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.

Author Contributions: Conceptualization, V.D.; methodology, A.E.; investigation, A.E., I.K. and C.M.; data curation, A.E. and P.C.; writing—original draft preparation, V.D; writing—review and editing, P.C.; Supervision, V.D. and A.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call "Collaborative Innovation Formations" (eMT cluster) project code: ΓΓ2CL-0356133.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data included in this study are available to researchers upon request.

Acknowledgments: We acknowledge Dimitrios Dafnis for the development of the biogas calculator application.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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