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Biogas production as a catalyst for energy autonomy and sustainable agriculture: A case study projection at Toro Impex Ltd

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Abstract. This research explores the establishment of a biogas plant at Toro Impex Ltd, converting pig manure and slaughterhouse residues into biogas for energy self-sufficiency and environmental benefits. It highlights the production of both electrical and thermal energy, with electricity contributing to the local grid and heat serving nearby industries. The study finds significant reductions in greenhouse gas emissions and odour pollution, alongside high-quality organic digestate for soil improvement. It also addresses socioeconomic impacts like job creation and local energy autonomy, offering a model for integrating waste management, renewable energy, and sustainable agriculture in rural contexts.

Keywords: energy self-sufficiency, agricultural waste to energy, environmental sustainability, circular economy

1. Introduction

In recent years, the agricultural and food processing industries have faced significant challenges related to energy consumption and waste management [1], [2]. This is particularly evident in rural industrial entities, which often lack a clear path for efficient energy use and sustainable waste management [3]. The agro-food industry, comprising pig farms and slaughterhouses, stands out as a sector with high energy demands and considerable waste production, necessitating innovative solutions to address these issues [4]. Pig farms and slaughterhouses are prime examples of this, as they require substantial amounts of thermal energy and power for various operations [5]. However, these industries often operate in remote areas where access to reliable and sustainable energy sources is limited. The lack of a clear path for energy and waste management not only poses operational challenges but also leads to increased environmental impacts [6] [7].

The processes involved in rearing pigs, slaughtering, and processing meat demand significant thermal energy and electricity [8]. For instance, maintaining optimal conditions in pig housing, including heating and ventilation, requires continuous energy input. Similarly, slaughterhouses utilize large amounts of energy for processes such as scalding, dehairing, evisceration, and cooling. Therefore, these facilities highlight the need for efficient energy management strategies to ensure operational sustainability and cost-effectiveness [9].

The energy dependency of agro-food industries on fossil-based energy resources such as natural gas and other conventional sources has been a significant concern [10]. This dependency has exposed these industries to various risks, particularly in the light of recent energy crises and price volatility [11]. The energy crisis in recent years has exacerbated these issues, highlighting the vulnerability of businesses that rely heavily on non-renewable energy sources [12]. The fluctuating availability and cost of fossil fuels have underscored the need for alternative, renewable energy sources that can provide greater stability and sustainability [13].

Renewable energy solutions, particularly those based on biogas, offer a viable pathway to reducing energy dependency and mitigating the risks associated with energy crises [14], [15]. By harnessing the energy potential of organic waste, pig farms and slaughterhouses can achieve greater energy independence and stability [16], [17]. This shift towards renewable energy not only addresses operational challenges but also aligns with broader environmental goals, including the reduction of GHG emissions [18].

A major challenge confronting the contemporary agro-food industry involves addressing climate change, necessitating substantial mitigation efforts targeting the reduction of emissions of greenhouse gases (GHGs) [19], [20]. The adoption of biogas systems in pig farms and slaughterhouses can significantly contribute to reducing GHG emissions. Biogas production through anaerobic digestion captures methane, a potent GHG, that would otherwise be released into the atmosphere from untreated waste. The use of biogas as a renewable energy source further displaces fossil fuel consumption, leading to additional reductions in CO2 emissions [21].

One promising solution to address the energy and waste management challenges in pig farms is the production of biogas [22]. Biogas, primarily composed of methane, can be produced through the anaerobic digestion of organic waste, such as pig slurry [23]. This process not only reduces waste but also generates renewable energy that can be used to meet the energy demands of pig farms and slaughterhouses [24].

The potential of biogas production from pig farms to achieve energy self-sufficiency warrants detailed analysis [25]. By assessing the amount of biogas that can be produced from pig slurry, fluid by-products from slaughterhouses, and other organic waste, it is possible to determine the extent to which this renewable energy source can meet the thermal and electrical energy needs of these facilities [16]. This analysis involves evaluating factors such as the quantity and composition of waste, the efficiency of anaerobic digestion processes, and the energy requirements of the farm and processing operations [26].

There are several case studies and examples of medium- and large-sized dairy farms that have real potentials [16] but have also successfully implemented biogas systems to achieve energy self-sufficiency [27]. These examples can provide valuable insights and lessons for pig farms and slaughterhouses looking to adopt similar solutions. For instance, some dairy farms have integrated biogas production with their energy systems, using the generated biogas to power generators and produce electricity, as well as to provide thermal energy for heating purposes. These solutions not only enhance energy self-sufficiency but also contribute to reducing greenhouse gas (GHG) emissions [28].

Reduced reliance on fossil fuels leads to lower energy costs and enhanced energy security. Additionally, the production and use of biogas can create new revenue streams for pig farms and slaughterhouses, further incentivizing the adoption of this technology [29]. The combination of environmental and economic benefits makes biogas a compelling solution for sustainable energy and waste management in the agro-food industry [30], [31], [32], [33].

Therefore, by evaluating the biogas potential of pig farms and analysing successful case studies from other sectors, it is possible to develop effective strategies for renewable energy adoption. The transition to biogas systems not only addresses immediate operational challenges but also aligns with broader goals of reducing GHG emissions and enhancing energy security. As the agro-food industry navigates the complexities of energy and waste management, biogas offers a viable and sustainable solution that can transform the energy landscape of rural industrial entities.

The primary objective of this paper is to explore and demonstrate the feasibility of establishing energy self-sufficiency within a rural agro-food industrial entity, specifically focusing on a pig farm and its associated meat-processing facilities. The study aims to assess how the utilization of pig manure as a feedstock for biogas production can meet the energy needs of a multifaceted agro-industrial operation. This exploration extends to the potential benefits of biogas production in terms of environmental impact, economic sustainability, and social contributions within the local community.

More specifically, the objectives of this research include:

1. Evaluation of pig manure if it can produce sufficient biogas to supply the necessary electrical and thermal energy required for the entire operation of the

farm, slaughterhouse, and other associated facilities, thus achieving complete energy independence.

2. Assessment of whether biogas production can mitigate odour pollution and reduce greenhouse gas emissions, thereby decreasing the environmental footprint of the pig farming operation.

3. Assessing the feasibility of selling surplus electricity generated from biogas back to the grid and providing excess thermal energy to neighbouring industrial sites with high heat demand, thus enhancing economic returns and fostering regional industrial synergy.

4. Examining the quality of the digestate-produced post-fermentation in the biogas plant, focusing on its potential as a high-quality organic fertilizer that can improve soil health and significantly reduce the reliance on chemical fertilizers.

5. Exploring how the establishment of a biogas plant could create new job opportunities, contribute to local employment, and support the creation of a local energy community that promotes energy autonomy, reduces dependency on energy imports, and stabilizes the local economy.

The following hypotheses guide this research:

1. Pig manure and slaughterhouse residuals, as an input material, can generate sufficient electrical and thermal energy through biogas production to support the diverse operations of the enterprise, thereby achieving energy self-sufficiency.

2. The biogas plant will significantly reduce odour pollution and prevent substantial GHG emissions, thus avoiding major environmental impacts and contributing positively to the local ecosystem.

3. The electricity generated in excess of the farm's own consumption will be sold to the grid, while the thermal energy will be used to meet the demands of neighbouring industrial sites, which have also high heat requirements, creating an additional revenue stream and promoting local industrial cooperation.

4. The post-fermentation digestate will be a high-quality matured organic material, providing an excellent nutrient source for crops when applied to fields, positively impacting soil quality compared to raw manure, radically reducing the use of chemical fertilizers.

5. The biogas plant will create new job opportunities, and it creates a local energy community, reducing reliance on imported energy, fostering energy autonomy, and resulting in a more stable energy supply for the local economy.

These hypotheses will be tested through a combination of qualitative and quantitative methods, based on case study, energy production simulations, environmental impact assessments, and economic feasibility analyses. The outcomes of this research are expected to provide valuable insights into the potential of biogas technology as a sustainable energy solution for rural agro-industrial operations, particularly in regions facing similar challenges and opportunities.

2. Materials and methods

In the present research, we approached the topic from energetic, environmental, economic, and social aspects, analysing with quantitative and qualitative methods the impact of a biogas plant on a specific company in the agro-food industry, using a real framework of a Toro Impex Ltd site in Romania, as it follows:

1. In the first step, the amount of input materials (m^3) was determined based on the number of livestock in daily, monthly, and annual breakdowns. Slurry production comes from three sources: a.) liquid manure from pig farm, b.) liquid manure from cattle breeding, and c.) wastewater and fluid by-products from slaughterhouse activities.

a.) The pig manure volumes were calculated based on the following formula (1) in a daily breakdown, and considering breeding cycles, it can also estimate weekly, monthly, or annual yield:

$$HHs = A * HT^n/1000, \qquad (1)$$

where: HH_s represents the slurry yield in the case of pigs, A represents the livestock (3,500 in one breeding cycle), and HT^n represents the daily slurry production expressed in kilograms. The daily slurry production of the pigs was calculated weighted by their body weight; as a result, we can present a daily slurry production dynamic. Furthermore, the quantitative data of the daily manure production are expressed in tons in order to make the quantitative data easier to read and visualize.

b.) The second formula (2) was used to determine the quantitative yield of liquid manure from cattle breeding, broken down daily, and then we can also estimate weekly, monthly, or annual yield:

$$HHsz = A * HT^n/1000, \qquad (2)$$

where: HH stands for liquid manure yield, calculating with an average livestock of 60 animals, and HT^n means the daily liquid manure production expressed in kilograms. With the previous approach, the manure production volumes were calculated with the cattle body weight, expressed in tons, in order to make the quantitative data easier to read and visualize.

c.) The quantitative determination of wastewater and other fluid by-products from slaughterhouse activities (m^3/day) are based on the plant's processing capacity depending on the number and average weight of the animals processed per day (t/day); see formula 3:

$$Fsk = S * \text{á}.t./1000, \qquad (3)$$

where: F_{sk} means the volume of processed pigs (t/day), and S means the number of pigs (as an average 200 pigs/day are processed with an average weight of 98 kg, expressed in ton).

The processing of cattle was expressed with the same approach, with formula (4):

$$Fszk = Sz * á.t./1000, \quad (4)$$

where: F_{szk} means the processed cattle capacity (t/day), Sz means the number of cattle (50 every day of the year except for the days off), and the average weight of the animals is 300 kg, expressed in tons.

The following formula is used to determine the daily wastewater production of the slaughterhouse (5):

$$Vsz = (Fsk * 2) + (Fszk * 5), \quad (5)$$

where: V_{sz} represents the daily wastewater production of the slaughterhouse, F_{sk} means processed pig capacity, and F_{szk} means processed cattle capacity. Based on the study done by Ungureanu [34] at the company, the former is multiplied by a value of 2 while the latter by a value of 5. The sum of the two above-mentioned types of animal processing gives the total amount of daily wastewater production.

The following formula (6) is used to determine the amount of biogas that can potentially be produced from the daily amount of wastewater (m^3):

$$SZb = Vsz * 0.2, \quad (6)$$

where: S*Zb* represents the amount of biogas that can be produced from wastewater, multiplying the Vsz value by a value of 0.2; according to [34], the amount of biogas expressed in m^3 can be determined.

The following formula (7) is used to determine the estimated daily amount of biogas (m^3) produced by the biogas plant:

$$BTn = [(HHs + HHsz) * 400] + SZb, \quad (7)$$

where: BT_n represents the daily biogas production expressed in cubic meters. The sum of HH_s and HH_{sz} is multiplied by a value of 400. According to Pauda [35], 0.4 m^3 of biogas can be produced from 1 kg of slurry under suitable fermentation conditions. Since the amount of slurry is expressed in tons, we use the value of 400. After that, the amount of biogas produced from wastewater is added to the amount of biogas produced from slurry.

2. The production of a.) electricity and b.) thermal energy of the biogas plant was determined.

a.) The study of Akbulut (2012) serves as the basis for determining the production of electricity, according to which 2.14 kWh can be produced from 1 m^3 of biogas. The following formula (8) can be used to calculate the amount of electricity production expressed in MWh in a daily breakdown, which can later be calculated in weekly, monthly, and yearly breakdowns:

$$VeMWh = Bg * 2.14/1000, \tag{8}$$

where: V_{eMWh} expresses the quantity of electricity in MWh, B_g denotes the quantity of biogas (m^3); dividing by 1,000 is necessary to convert the 2.14 kWh value into MWh.

MWh is an internationally recognized unit of measurement for electricity, but in some countries, such as in Hungary, practice shows that MJ and GJ are also commonly used. Therefore, the amount of electricity yield was also calculated in these forms based on [36]. The formula for converting to MJ is (9):

$$VeMJ = Bg * 22, \tag{9}$$

where: V_{eMJ} expresses the amount of electricity in MJ, and B_g indicates the amount of biogas (m^3), which must be multiplied by the value of 22, as described in the study of [36]. To express in GJ, the value of MJ is divided by 1,000; in the formula, V_{eGJ} expresses the amount of electricity in GJ (10):

$$VeGJ = Bg * 22/1000 \tag{10}$$

According to Akbulut [37], his study serves as a basis for determining the daily thermal energy production, according to which 1 m^3 of biogas results in the production of 2.47 kWh of thermal energy. The formula (11) for the calculation of the produced thermal energy is the following, which can also be expressed in other breakdowns such as weekly, monthly, or yearly:

$$HeMWh = Bg * 2.47/1000, \tag{11}$$

where: H_{eMWh} denotes the production of heat energy. We divide the result of the product of the reference value 2.47 and B_g by 1,000 to express kWh in MWh. On the other hand, when calculating the result of the available heat energy that approximates the reality, 10% must be deducted from the H_{eMWh} value, as this is used by the plant for its own operation.

3. The degree of energy self-sufficiency was analysed based on the heat and electricity usage analysis of the examined company family, and the company provided the data on the group's electricity and natural gas consumption (MWh).

In terms of electricity, in addition to data on the energy consumption of meat processing and slaughterhouses, data on other points of consumption were also provided. The consumption indicators come from previous years in a monthly breakdown and in the case of electricity also in a daily breakdown. Also, it was estimated as to what extent it could provide energy for the other economic activities of the surrounding industrial park: a board price and drying plant, a milk factory, etc.

4. The amount of greenhouse gases from the livestock by-product of pig fattening, and its impact on the environment, expressed in tons/year in relation to carbon dioxide (CO_2) and sulphur dioxide (SO_2). The calculation was realized based on reference values from the study done by Dourmad [38], simultaneously with eutrophication (algae and swamping of waters). This method used the following formula (12):

$$Kh = S * á.t. * r.é./1000, \tag{12}$$

where: K_h represents the annual load on the environment (e.g. CO_2), S represents the number of pigs (11,500), á.t. denotes the average weight per animal (70 kg), and r.é. denotes the reference values described in the aforementioned study, based on 1 kg pig live weight. The division is necessary so that the value is expressed in tons for an easier understanding.

Another greenhouse gas, methane (CH_4), also requires increased attention. Quantifying its release into the atmosphere is very difficult, so we approach it from the point of view that the raw material used in the biogas plant (e.g. pig slurry) can release around 60% of methane during optimal intensive fermentation processes [39]. Of course, this can only be achieved in fermentation units, as liquid manure stored outdoors does not release such a large amount into the atmosphere.

5. The investment budget was based on a detailed study [37].

The realization of the construction of the biogas plant requires two types of investment: one is the so-called capital expenditure (CAPEX), which the company pays once during the implementation process, and the other investment is operational expenditure (OPEX), which must be continuously financed beyond the construction of the plant [40].

6. Calculation of return and yield data based on the cost of the investment and the value of the heat and electricity produced. Before the start of the investment, the net present value (NPV) must be calculated, which can be used to decide whether or not the investment is worthwhile. If NPV > 0, then we can implement the investment, whereas if < 0, then we do not implement it because it will be unprofitable. The formula for its calculation is (13):

$$NPV = \sum_{t=0}^{N} \frac{C_n}{(1+r)^n} - C_0, \tag{13}$$

where: C represents the sum of cash flows, n denotes each period, N represents the holding period, and r represents the desired target yield or denotes the required rate of return [41]. Calculating the payback period, the Bioenergy for Business Software [42] was used with a 25-year perspective.

7. Carrying out and presenting the economic calculations of sustainable biogas operation.

8. Examination of the social, health, and sustainability effects of the investment on the local and microregion.

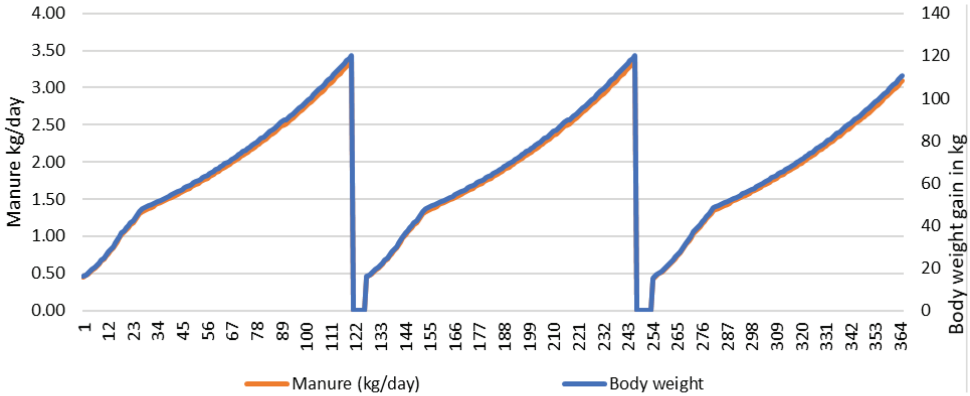
3. Results and discussion

3.1. Biogas production assessment

Firstly, we are going to present the research site, namely the Toro Impex Ltd, established in 1991, whose main activity was the operation of a slaughterhouse and meat processing plant in the village of Lemnia in the north-eastern part of Covasna County in Romania. In 2007, thanks to a SAPARD co-financed investment project, the company constructed a new slaughterhouse. The modern enterprise began to develop rapidly into a modern pig, sheep, and cattle slaughterhouse and processing plant that meets the expectations. Additionally, between 2014 and 2016, a pig farm was also constructed with a capacity of 3,600 pigs, which can realize 3 breeding cycles annually. Along this, cattle breeding takes place within this agro-food company. Agricultural activities are also part of the company's activities, growing crops on more than 100 hectares. Livestock-feeding activities produce main field crops such as corn, wheat, and other cereals, and tens of hectares of mowing fields are used for the seasonal grazing of animals. The machine park is well equipped, but in order to maintain it, it also operates a well-equipped service workshop with qualified personnel. Thus, they undertake to repair the equipment of the farmers in the area [43].

At the pig-breeding site, 3,600 pigs are raised to slaughter weight in each cycle, which means from an initial state of 16–25 kilograms to a state of 90–120 kg in around 100 days, amounting to 10,800 pigs per year. Between each cycle, there are a few days (approx. 7) during which there are no pigs in the buildings, which is when the area is sanitized and preparations are made for the arrival of the next round of pigs. The number of empty days can be increased up to 25 days per year.

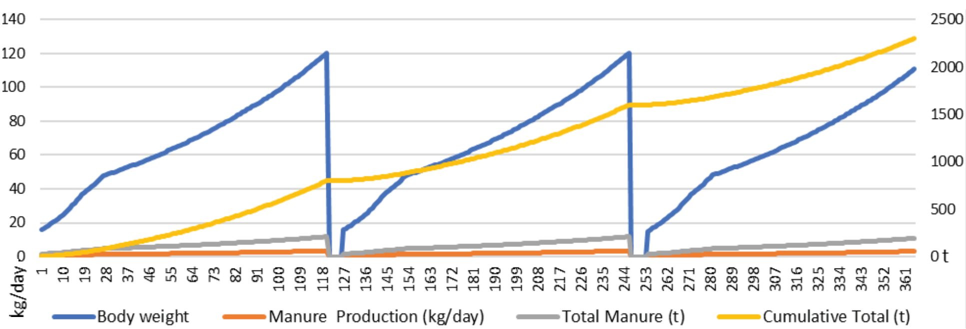
According to [44], we know that an average pig weighing 70 kg produces 2.09 kg of liquid manure per day. Using the rule of three, it can be calculated that a pig with an initial weight of 16 kg entering the farm produces 0.447 kg of liquid manure per day. The daily body weight gain per pig is shown in parallel with the daily slurry production in the diagram below (*Figure 1*).



Source: authors' calculation

Figure 1. The annual trend of pig body weight development and slurry training

On the farm level, the daily manure production of pigs in an annual projection is illustrated in *Figure 2*. The weight of the pigs from the beginning of the breeding cycle to the 18th day grows 1.05 kg/day, from the 19th to the 27th 1.03 kg/day, and from the 28th day to slaughter weight 1.01 kg/day [45]. Knowing the average daily weight of the pigs and the amount of daily liquid manure production calculated from this using the rule of three, together with the empty days, approximately 2,304.52 tons of liquid manure is produced as a by-product of the 10,800 pigs.



Source: authors' calculation

Figure 2. Annual dynamics of the pigs' body weight gain and liquid manure production

Based on our research, through the following steps, we designed the biogas production at Toro Impex Ltd, as well as the potential energy and power consumptions:

1. Preparation of raw materials: pig and cattle manure, silage and agricultural waste, and wastewater from the slaughterhouse are collected and pumped to the pre-storage.

2. Pre-treatment and storage: The pre-treated fluid manure is placed in a solid biomass tank, where it undergoes further processing. The material is processed into a homogeneous mixture; the solid biomass is processed with an energy consumption of 11 kWe.

3. Fermentation units: The mixture is sent to the first fermentation unit, where anaerobic fermentation takes place at a temperature of 44 °C. During fermentation, microorganisms break down organic materials, producing biogas and fermentation residues.

4. Secondary fermentation: The biogas and the fermentation residue pass on to the second fermentation unit, where the decomposition process continues at 38 °C, with an additional 18.5 kWe of energy consumption. This stage is used to increase the yield of biogas.

5. Fermentation tank: fermented residues are sent to a large fermentation tank, where the final decomposition processes take place. The entire process requires an energy consumption of 30 kWe.

6. Biogas storage and utilization: the generated biogas is collected in a biogas storage tank with a capacity of 250 m^3. The stored biogas can be used for various purposes.

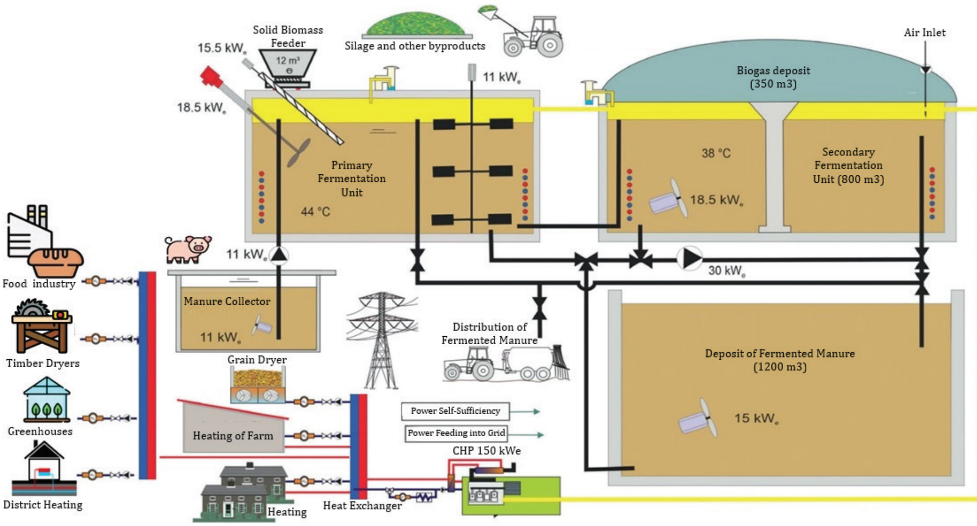
7. Electricity production: biogas is burned in a cogeneration (CHP) unit, which produces electricity and heat. The cogeneration unit operates with a total capacity of 450 kW, of which 150 kWe of electricity and 300 kWth of heat energy are generated.

8. Electricity and heat distribution: the generated electricity is used in farms and slaughterhouses, and the leftover will be fed into the electrical grid for use by consumers such as residential buildings, industrial facilities in surroundings, and public institutions. The generated heat is used in heating systems such as district heating networks.

9. Utilization of fermented residue: The solid and liquid materials remaining after fermentation are distributed to agricultural lands, where they serve as a valuable soil conditioner, improving soil fertility.

In summary, *Figure 3* shows the complex process of biogas production, which includes the preparation of raw materials, fermentation, storage and utilization of biogas, and the environmentally friendly treatment of residual materials.

The results of the annual calculation of the daily biogas production of 3,600 pigs raised at the same time show that an average of 2,525.48 m^3 of biogas is produced per day. The average of the weekly biogas generation is 17,678.36 m^3, while the annual data show a 921,800.2 m^3 of biogas production.

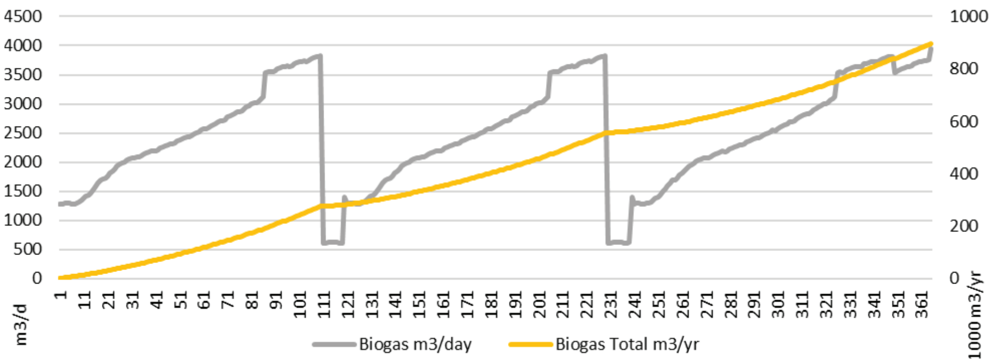


Source: authors' calculation

Figure 3. Flowchart of the biogas production and energy consumption

The breeding of approximatively 60 cattle, based on the study of [46], produces 29.5 kg of liquid manure per individual per day, which means 1.77 tons of liquid manure per day in total, an estimation also confirmed by the farm. This amount of liquid cattle manure produces 720 m^3 of biogas per day, 5,040 m^3 per week, 21,600 m^3 per month, and 262,800 m^3 per year.

The slaughterhouse and the meat-processing plant use a significant volume of hot water during their operation, and as a result the generation of wastewater is outstanding. Based on realistic data provided by the company, the plant has a daily processing capacity of 200 pigs and 50 cattle. The average weight of 200 pigs going to the slaughterhouse is 98 kg while that of 50 cattle is 300 kg, which means 19.6 tons of processed pigs and 15 tons of cattle per day. In order to determine the resulting daily amount of wastewater, the weight of pigs must be multiplied by 2, while the weight of cattle must be multiplied by 5 [47], based on which 114.2 m^3 of wastewater is generated (the slaughterhouse does not operate on weekends). According to [34], approximately 0.2 m^3 of biogas can be produced from 1 m^3 slaughterhouse wastewater with proper fermentation. Projected for the plant in Lemnia, this means 22.84 m^3 per day, 114.2 m^3 per week, 525.32 m^3 per month, and 5,961.24 m^3 per year of biogas production. In total, it means a biogas production of an average of 2,479.84 m^3/day, an average of 75,428.37 m^3/month, and 905,140.55 m^3/yr. The production dynamic of the biogas can be seen in the graph below (*Figure 4*) broken down into days in annual terms.



Source: authors' calculation

Figure 4. Daily and cumulative annual dynamic of biogas production

3.2. Assessment of energy and power consumption

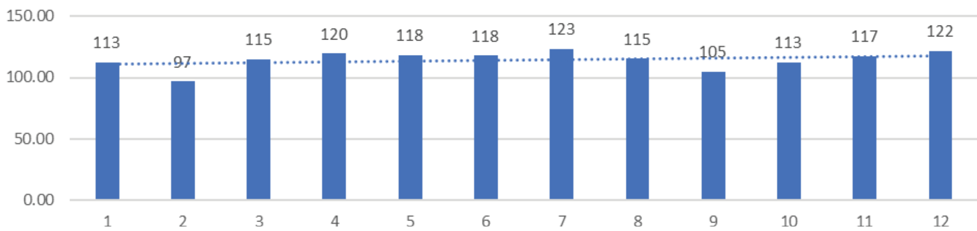
The company provided accurate data on the electricity and gas consumption of the slaughterhouse and meat-processing plant (*Table 1*).

Table 1. Annual power consumption of the company in total and in different consumption locations (MWh)

Location	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Bretcu	0.35	0.54	0.43	0.45	0.70	0.42	0.41	0.33	0.45	0.72	0.25	0.42	**5.47**
Oituz	6.46	7.79	7.80	7.98	6.20	7.07	6.25	8.20	6.30	7.70	6.88	7.42	**86.05**
Bretcu 2	3.20	3.21	3.00	2.72	3.02	2.22	2.86	3.11	2.60	2.68	3.21	3.42	**35.25**
Târgu Secuiesc	1.64	0.38	1.20	1.32	0.90	2.35	2.63	0.88	1.34	2.88	2.11	2.99	**20.62**
Lemnia 1	2.00	1.69	2.20	2.30	2.45	3.01	3.30	2.45	1.98	2.23	3.12	3.22	**29.95**
Lemnia 2	1.50	1.00	1.34	1.50	1.70	1.50	1.66	1.21	1.32	1.43	1.73	1.42	**17.31**
Mereni	2.45	2.07	2.22	2.45	2.80	2.62	2.69	2.40	2.32	2.86	2.02	2.86	**29.76**
Lemnia 3	95.00	80.10	97.00	101.00	100.68	98.63	103.38	96.80	88.30	92.20	98.13	99.76	**1,150.98**
Total	**112.60**	**96.78**	**115.19**	**119.72**	**118.45**	**117.82**	**123.18**	**115.38**	**104.61**	**112.70**	**117.45**	**121.51**	**1,375.39**

Source: Toro Impex Ltd

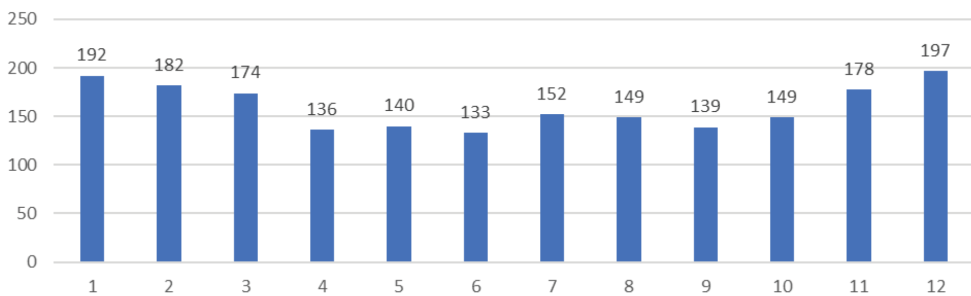
Broken down into 12 months of the year, the electricity consumption of the above-mentioned locations can be seen in *Table 1*. On average, the consumption is 114.62 MWh per month, and summing up the electricity consumption of the months on an annual basis, the result is 1,375.39 MWh. Of this energy use, the slaughterhouse and the meat processor consume 1,128 MWh hours (*Figure 5*).



Source: authors' calculation

Figure 5. Monthly power consumption at Toro Impex Ltd

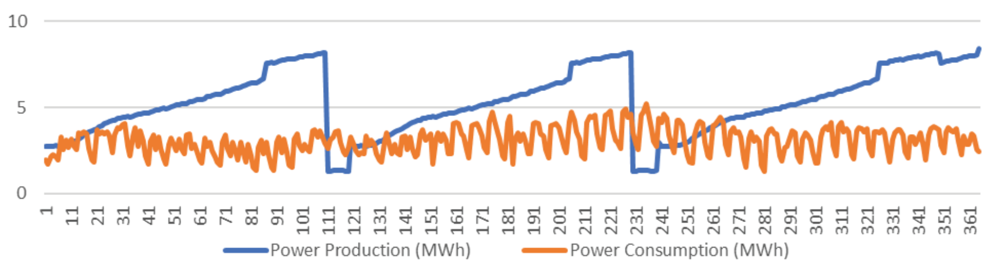
For heating purposes, the slaughterhouse and the meat processing plant currently use natural gas (*Figure 6*), which generates an average monthly consumption of 159.88 MWh, as can be seen in the diagram. In total, 1,918.56 MWh of natural gas is used annually.



Source: authors' calculation

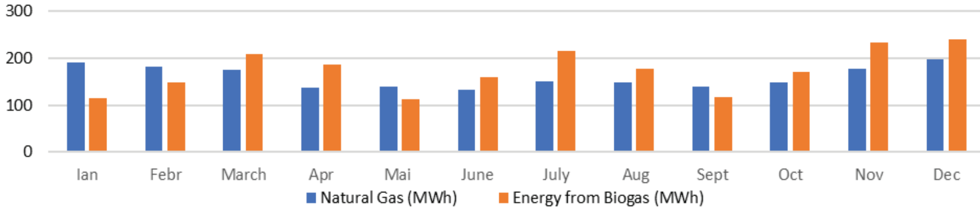
Figure 6. Monthly natural gas consumption (MWh) at Toro Impex Ltd

The potentially produced amount of biogas (m3) can be converted into electricity or thermal energy. The energy yield of biogas that can be produced in a daily breakdown is 4.04 MWh/day and in annual terms approximately 1,917 MWh/year (*Figure 7*). The following figure (8) shows a monthly breakdown of the thermal energy potentially produced from biogas and the demand for natural gas for energy production, expressed in MWh.



Source: authors' calculation

Figure 7. Daily and annual power consumption and production in MWh



Source: authors' calculation

Figure 8. Thermal energy demand covered by natural gas and potentially produced biomass in MWh

3.3. Assessment of biogas investment

Table 2 summarizes the elements required for the operation of the biogas plant. The costs listed in the table include the capital costs (CAPEX) of the biogas plant, which means the initial investment costs required to establish the plant. These costs cover physical assets, infrastructure, and construction works alike. The details of each item are as follows:

1. Assets: EUR 371,956.39

– This amount includes the basic equipment and machinery required for the operation of the biogas plant. These may include the various mechanical and electrical systems that ensure the efficient and safe operation of the plant.

2. Earthwork/Landscaping: EUR 33,896.76

– The costs of earthworks and landscaping include the work necessary to prepare the construction of the plant. This includes site preparation, foundation, and proper drainage systems.

3. CHP Turbine: EUR 263,305.17

– Costs of a combined heat and power (CHP) turbine. The CHP unit plays a key role in the use of biogas, as it enables the efficient production of electricity and heat from biogas.

4. Heating network: EUR 75,662.41

– The costs of building the heating network. This system is used to transport the thermal energy produced by the CHP unit, which is used to heat the facility and possibly the surrounding community.

5. Electricity connection: EUR 15,132.48

– This amount includes the costs of connecting the biogas plant to the electricity system, including the installation of the necessary cables and transformers.

6. Primary fermenter: EUR 151,324.81

– Costs of the primary fermentation unit. In this equipment, the first phase of anaerobic fermentation takes place, during which the production of biogas begins.

7. Secondary fermenter: 211,854.74 EUR

– Costs of the secondary fermentation unit. This unit performs the second phase of fermentation, in which the efficiency of biogas production continues to increase.

8. Fermentate tank: EUR 90,794.89

– Costs of a deposit for storing fermentation residues. This container ensures the safe storage and subsequent utilization of the remaining materials.

9. Pump units: EUR 121,059.85

– Costs of various pumps and pumps used to move raw materials, fermentation residues, and biogas between different parts of the plant.

Total: 1,334,987.50 EUR

The total investment cost, which includes all the items mentioned above, is detailed in *Table 2*. This amount shows the total capital investment required to establish the biogas plant.

These costs are crucial for the successful installation and operation of a biogas plant, as they provide the necessary infrastructure and equipment for the efficient production and utilization of biogas. An accurate definition and optimization of individual items is essential to ensure the economic viability of the project.

Table 2. CAPEX of the biogas plant

CAPEX	**EUR**
Equipment	371,956.39
Earthwork/Landscaping	33,896.76
CHP Turbine	263,305.17
Heating demand	75,662.41
Power connection to grid	15,132.48
1st fermentation	151,324.81
2nd fermentation	211,854.74
Deposit of fermented residuals	90,794.89
Pump stations	121,059.85
Total	1,334,987.50

Source: authors' calculation

Table 3 shows the annual costs beyond the construction of the plant, expressed in euros:

– Personal expenses: 14,500.00 EUR

This amount includes the full annual cost of staff wages, benefits, and other related expenses required to operate the plant.

– Biogas CHP Maintenance: 1,499.62 EUR

This cost is the sum of the annual expenses related to the maintenance of the biogas cogeneration plant (CHP). This includes replacement of parts, repairs, and preventive maintenance activities.

– Fermenter maintenance: 2,999.25 EUR

The fermenter, which performs the anaerobic fermentation process, requires regular maintenance. This item includes cleaning, replacement of parts, and other maintenance tasks.

– Control and inspection: EUR 2,250.00

This amount covers the operating and maintenance costs of the control and monitoring systems of the biogas plant. This includes software updates, hardware maintenance, and regular checks.

Total: 21,250.00 EUR

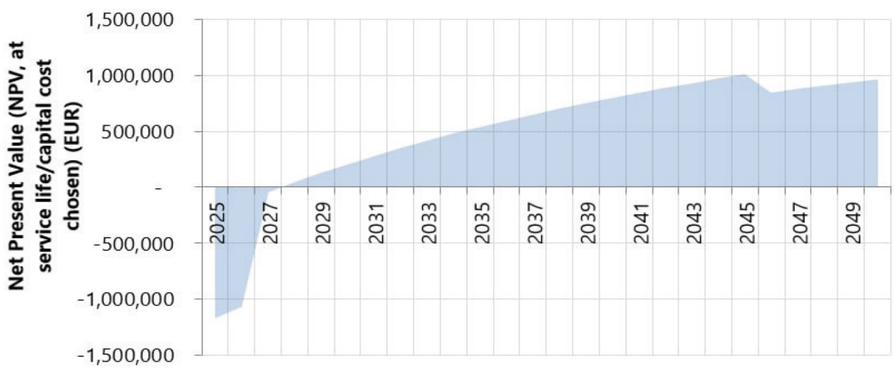
The above costs reflect in detail the main expenses that are necessary for the annual operation and maintenance of the biogas plant.

Table 3. OPEX of the biogas plant

OPEX	**EUR/Yr**
Personal costs	14,500.00
Maintenance of Biogas CHP	1,499.62
Maintenance of fermentation	2,999.25
Monitoring and control system	2,250.00
Total	21,250.00

Source: authors' calculation

The calculation of the payback period of the biogas plant was made possible by the use of the Bioenergy for Business Software. Including all costs (also annual maintenance costs), the payback period can be set at 3.2 years, as shown in the diagram created below, as well as the net present value was calculated for a period of 25 years; its dynamic is shown in *Figure 9*.



Source: authors' calculation

Figure 9. Calculation of the payback period and net present value in 25 years dynamic

3.4. Assessment of the environmental impact of the investment

The table below (4) shows the amount of CO_2, SO_2, and CH_4 released into the atmosphere and the degree of eutrophication in the case of untreated slurry, expressed in tons on an annual basis; in other words, with the establishment of the biogas plant, 1,812 t/year CO_2, 35 t/year SO_2 greenhouse gas enters the atmosphere, and the eutrophication of waters would decrease by 15 t/year compared to the (current) state before the establishment of the biogas plant.

On an annual basis, during the operation of the biogas plant, an average of 1,487.63 m^3 per day and approximately 364,345 t/yr of methane are produced. In the case of liquid manure stored in untreated form, methane emissions would not be as high, but a large part of this amount would be released into the atmosphere, further increasing the greenhouse effect.

The fermented residue produced during the production of biogas can be used as a valuable soil conditioner, which improves the fertility of agricultural land with its high nutrient content. In addition, biogas plants can contribute to improving waste management by recycling agricultural and municipal waste, thereby reducing the burden on landfills and environmental pollution from waste [48].

The establishment of the biogas plant leads to the creation of new jobs, which contributes to the revitalization of the local economy and the reduction of unemployment. The workforce needed to run the plant can be sourced from local residents, thereby strengthening the economic stability of the community. In addition, during the establishment of the plant, local businesses can also benefit from the construction and maintenance work, which further strengthens the local economy.

The biogas plant can significantly contribute to alleviating odour problems in the environment. During the fermentation processes, raw materials such as liquid manure and sewage decompose anaerobically, so no unpleasant odour is produced. This can result in a significant improvement in the quality of life of local residents, especially those living in the immediate vicinity of the plant.

Table 4. The effect of raw slurry on the environment

	Total value for Toro Impex Ltd t eq.	**Ref. value for 1 kg life weight *[49]***
Carbon dioxide (CO_2)	1,812	2.251
Sulphur dioxide (SO_2)	35.42	0.044
Methane (m^3 CH_4)	364,345	
Eutrophication	15,295	0.019

Source: authors' calculation

The operation of the biogas plant provides a sustainable source of energy that can cover the plant's own heating and electricity needs and can even produce surplus energy. This can lead to reduced energy use and reduced demand for fossil fuels. Self-sustainable energy supply reduces dependence on external energy sources, increases energy security, and contributes to combating climate change by reducing greenhouse gas emissions.

4. Conclusions

Building on the hypotheses, the establishment of a biogas plant at Toro Impex Ltd offers a comprehensive solution to meet the company's energy needs while simultaneously addressing environmental, economic, and social objectives. The utilization of pig manure and slaughterhouse residues as primary feedstock for biogas production aligns with the enterprise's goal of achieving energy self-sufficiency. The conversion of these organic materials into biogas is expected to generate sufficient electrical and thermal energy to support the diverse operations of the enterprise. This energy autonomy reduces the dependency on external supply, thereby enhancing the company's resilience to energy market fluctuations and supply disruptions.

In addition to meeting the company's internal energy demands, the biogas plant is projected to significantly mitigate environmental impacts. One of the most critical environmental benefits is the substantial reduction in odour pollution, a common issue associated with pig farming and slaughterhouse operations. The anaerobic digestion process not only controls these odours but also prevents the release of large quantities of greenhouse gases (GHGs), particularly methane, into the atmosphere. This reduction in GHG emissions contributes to the mitigation of climate change, positioning Toro Impex Ltd as a responsible entity that actively participates in environmental stewardship and local ecosystem preservation [50].

The energy generated by the biogas plant extends beyond the company's immediate needs. The hypothesis posits that any excess electricity produced will be fed into the national grid, thus creating a valuable additional revenue stream for Toro Impex Ltd. This surplus electricity generation not only supports the financial viability of the biogas plant but also contributes to the broader energy infrastructure by providing clean, renewable energy to the grid. Additionally, the thermal energy generated, which might exceed the farm's requirements, can be utilized by neighbouring industrial sites with high heat demands. This strategic use of thermal energy fosters industrial cooperation within the local community and creates opportunities for economic synergies, further strengthening the local economy.

The post-fermentation digestate, a by-product of the biogas production process, offers substantial agricultural benefits, aligning with the hypothesis that it will serve as a high-quality, mature organic material for crop fertilization. The application of this nutrient-rich digestate to agricultural fields has the potential to significantly improve soil quality compared to the use of raw manure. By enhancing soil fertility, the digestate reduces the need for chemical fertilizers, which not only lowers agricultural input costs but also minimizes the environmental impacts associated with synthetic fertilizers such as soil degradation and water contamination. This shift towards organic fertilization represents a significant advancement in sustainable agricultural practices within the region.

Moreover, the biogas plant is expected to generate new employment opportunities, which aligns with the hypothesis that it will contribute to the creation of a local energy community. The jobs created during both the construction and operational phases of the plant will provide economic benefits to the local community, reducing unemployment and enhancing economic stability. The development of a local energy community, supported by the biogas plant, fosters energy autonomy by reducing reliance on imported energy [51]. This autonomy not only stabilizes the local energy supply but also positions the community to better manage energy resources in times of economic or geopolitical uncertainty.

In conclusion, the biogas plant project at Toro Impex Ltd is poised to deliver on the hypothesized benefits, including achieving energy self-sufficiency, reducing environmental impacts, generating additional revenue, improving soil quality, and fostering local economic development. The integration of these outcomes underscores the strategic importance of the biogas plant as a cornerstone of sustainable development for the company and the surrounding community. By leveraging the plant's potential to transform waste into valuable resources, Toro Impex Ltd will not only enhance its operational efficiency but will also contribute to the long-term sustainability and prosperity of the region.

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