SMART-FARMS: Transforming chicken litter into a reliable source of energy through anaerobic co-digestion

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Abstract

According to FAO (2016), there are approximately 21.3 billion heads of chicken constantly reared for meat and eggs worldwide. In a chicken farm located in Western Slovakia about 160,000 chickens are raised to produce meat. As much as 360 Mg month^{-1} of chicken litter are produced in the farm. An experimental study provided key information on the performance of the anaerobic system in different operational conditions. Thus, the addition of a carbon rich co-substrate (OLR = 2 g VS L^{-1} d^{-1}, AcoD ratio = 1:1) and water (SRT = 150 d) improved significantly the performance of reactors, increasing methane yields and mitigating ammonia accumulation in the long term. SBP averaged 704 m^3 kg^{-1} VS for the feedstock mixture chicken litter-waste oil. The parameters during best reactor performance were used for the technological design of the biogas plant.

In the current operational scheme, the poultry farm spends on average about 121 538 € year^{-1} on energy, comprised of 9639 € for electricity (113.4 MWh) and 111899 € for natural gas (319 200 Nm^3). Within the concept of SMART-FARMS, the biogas plant is able to provide a reliable source of energy based on the amount of manure produced in the farm itself, covering all the energy needs of the poultry farm and generating a surplus of about 123540 € year^{-1}. Furthermore, it contributes to the generation of 8 new local jobs and to making industrial farming more sustainable.

Keywords
Anaerobic co-digestion, biogas, chicken litter, poultry farm, smart-farms, waste oil

1. Introduction

In the last few decades, one of the most outstanding achievements of present world has been the rapid industrialisation of agriculture. This dynamic development in agriculture has been able to sustain the rapid human population growth which has occurred at the same time, and is the product of the strong investment of some countries in food production, industrial methods and techniques that have made it possible to reduce operational costs for raising agricultural animals such poultry, cattle and pigs. According to FAO (2016), there are approximately 21.3 billion chicken heads constantly reared for meat and eggs worldwide.

Poultry litter can lead to large productions of methane (CH_4) and nitrous oxide (N_2O), greenhouse gases with a global warming potential 25 and 310 times higher than CO_2, respectively. Additionally, if the manure is poorly managed, the impact of other nutrients present in manure will contribute indirectly to the acidification process in soil and eutrophication of waters (Chávez-Fuentes et al., 2017). On the other hand, the high consumption of energy by poultry farms, especially of natural gas, indisputably place the question, whether animal manure could be used as a major source of energy for animal farms. Anaerobic digestion is one of the available technologies that can tackle the manure management and the energy needs of the poultry farm at once, promoting the transition from classical industrial farms into smart-farms. Therefore, it can be expected that anaerobic digestion will play a major role in the management of manure in future years.

This study aims to evaluate the technical potential of a poultry farm to cover its own energy needs, through anaerobic co-digestion of the chicken litter generated within the activities of the farm and a C-rich co-substrate. Moreover, it provides information on whether the operation of the anaerobic digester can be stable in the long term and overcome (resp. prevent) ammonia accumulation through anaerobic co-digestion. On the other hand, it estimates what the real outcomes of a full-scale biogas plant could be, within the concept of SMART-FARMS.

2. Current status of the poultry farm in Gbely, Slovakia

A modern industrial poultry farm located in the town of Gbely, in western Slovakia, raises chickens for sale. The poultry farm has 13 broiler sheds (also called poultry houses) and produces on average 160,000 heads of chicken in a growth cycle, which consists of 42 days. In this time, the chickens grow to their final size, weighing about 2700 g. Afterwards, the chickens are prepared for their journey to slaughterhouses and thus, the broiler sheds are emptied and cleaned. As much as 360 Mg of chicken litter is generated in the breeding process of the farm. Chicken litter is collected during the cleaning process of the sheds and placed temporarily in a manure pit within the poultry farm for its further transport and disposal by external partners. The transition period between every growth cycle is about 18 days, in which the broiler sheds are cleaned, disinfected and prepared for incoming chicks.

Regarding transport and disposal of chicken manure, the economic result is basically positive for the poultry farm, as the farm gets some money from the sales of chicken manure or at least does not have to pay for the waste management. Therefore, so far, an external partner is responsible for the complete waste management of the poultry farm, i.e. it carries out both internal and external transport, as well as the final disposal of the manure in a composting facility located nearby. Recently, a biogas plant in the surroundings has also expressed its interest on collecting the manure for anaerobic digestion.

However, an even more attractive option for the poultry farm could be the construction and operation of its own biogas plant, in order to reduce its energy needs. In fact, in cold-weather countries such as Slovakia, supplying heat to the farm can generate more operating costs than feeding of chicken, as climate control in poultry farms plays a very important factor in the breeding process. The heating system of the chicken farm is based on the combustion of natural gas. Thus, farm's average consumption of natural gas when broiler sheds are operated is about 2,500 and 1,200 $Nm^3\ d^{-1}$ in winter and transitional months, respectively. The annual consumption of heat is estimated at 450,000 $Nm^3\ d^{-1}$, which represents more than 250,000 €/a. A biogas plant could be able to supply the farm's own energy needs (natural gas, electricity and heat); executing simultaneously the waste management of manure.

Figure 1 One of the open-air storage pits for litter in the poultry farm of the case study

Moreover, taking into consideration that the poultry farm already counts with enough space for the building of digesters, silos and other operative buildings, as well as basic equipment such as a tractor-scraper, a bulldozer and dump trucks; it could be affordable to build and run a biogas plant in situ. Additionally, the implementation of a biogas plant would contribute to a more circular economy of the poultry farm, reducing greenhouse gas emissions (GHG) and generating more local jobs.

Table 1 Selected operational characteristics of the poultry farm

Number of chickens in a growth cycle	heads	160,000
Chicken litter produced in a growth cycle (42 days) Specific production of chicken litter 0.054 kg hd^{-1} d^{-1} [3] Dry matter (TS) for chicken litter 606 g TS kg^{-1} Organic dry matter (VS) for chicken litter 535 g VS kg^{-1}	 Mg Mg TS Mg VS	 360 184 158
Available amount of chicken litter in a day	Mg Mg TS Mg VS	6 3.6 3.2
Daily average consumption of natural gas, mainly for heating of broiler sheds (operational temperature 33 °C)		
In summer days (84 d) In winter days (84 d) Transitional weather (84 d)	Nm^3 d^{-1} (GJ d^{-1}) Nm^3 d^{-1} (GJ d^{-1}) Nm^3 d^{-1} (GJ d^{-1})	100 (3.4) 2,500 (87.1) 1,200 (41.8)
Daily average consumption of electrical energy (mainly lights, feeding system, exhaust and ventilation fans, pumps)	kWh d^{-1}	450
Estimated energy consumption for the operations of a complete calendar year (252 d)	MWh y^{-1} Nm^3 y^{-1} (GJ y^{-1})	113.4 319,200 (11 127)

3. Experimental study

Two bench-scale fully-stirred anaerobic reactors were operated under mesophilic conditions (37 °C) during 500 days. Anaerobic sludge from the stabilisation tanks of a wastewater treatment plant experiment was used as inoculum. The main substrate for both reactors was chicken litter with the characteristics shown in table 1. As co-substrate, raw glycerol from the production of biodiesel was dosed to one reactor and extra-virgin olive oil to the other. Olive oil was replaced by waste kitchen oil as lipid source.

The analyses of the soluble fraction (COD, VFA, TAN, NH_3, PO4-P) and the total fraction (TS, VS and LOI) were performed according to standard methods. The composition of biogas was measured with a gas analyser Geotechnical Instruments GA2000.

The experimental study provided key information about the performance of the anaerobic system in different operational conditions. Parameters such as solid retention time (SRT), organic loading rage (OLR), anaerobic co-digestion ratio (AcoD) and type of co-substrate varied during the experiment. Firstly, it was found that the addition of water helped to improve reactor performance by decreasing solid retention times (SRT) but it did not fully solve the problem of ammonia accumulation at higher organic loading rates (OLR). In fact, high OLR along with very low SRT can result in a collapse of the anaerobic system by causing *washing-out* of reactor's anaerobic biomass and its further overdosing.

On the other hand, the addition of a carbon rich co-substrate (AcoD ratio = 1:1) and water (SRT = 150 d), contributed to significantly improving the performance of reactors, increasing methane yields and mitigating ammonia inhibition on the long term. In the period from when reactors were operated at OLR = 2 g VS L^{-1} d^{-1}, the specific biogas production (SBP) averaged 516 and 704 m^3 kg^{-1} VS for the feedstock mixtures chicken litter-raw glycerol and chicken litter-waste oil, respectively. The results from the experimental study can be seen in table 2.

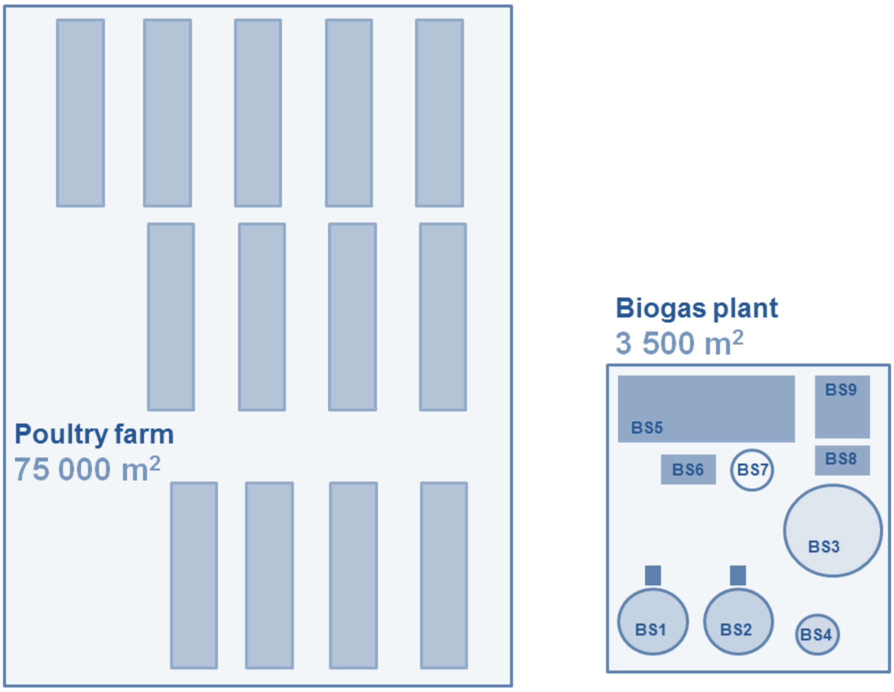
	Table 2 Selected technological parameters from the experimental study		
	General parameters		
1	Reactor and selected period	Between days 241 - 310	
2	Main substrate	Chicken litter	
3	Selected co-substrate	Olive oil/waste oil	
4	AcoD ratio	1:1	
5	Organic loading rate (OLR)	g VS L^{-1} d^{-1}	2
6	Solid retention time (SRT)	d	150
7	Volume of reactor's sludge	L	15
	Substrate input parameters		
1	Chicken litter	g d^{-1}	28
2	Olive oil/waste oil	g d^{-1}	15
3	Water	g d^{-1}	55
4	Chicken litter (VS = 53.5 %)	g VS d^{-1}	15
5	Olive oil/waste oil (VS = 100 %)	g VS d^{-1}	15
	Biogas parameters		
1	Daily biogas production	L d^{-1}	21.1
2	Specific biogas parameter (VS)	L kg^{-1} VS	704
3	Specific biogas parameter (R)	L L^{-1}	1.41
4	Methane content in biogas	% CH_4	63
5	Carbon dioxide content in biogas	% CO_2	36
6	Hydrogen sulphide concentration	ppm	2130
	Sludge parameters (Total and soluble fraction)		
1	Operational temperature	°C	37
2	pH	-	8.1
3	Chemical oxygen demand (COD)	mg L^{-1}	4670
4	Volatile fatty acids (VFA)	mg L^{-1}	1840
5	Total ammonia nitrogen (TAN)	mg L^{-1}	2230
6	Undissociated ammonia (NH3)	mg L^{-1}	300
7	Phosphate-phosphorous (PO_4-P)	mg L^{-1}	100
8	Total solids (TS)	g kg^{-1}	45
9	Volatile solids (VS)	g kg^{-1}	31
10	Loss on ignition (LOI)	%	68
11	Specific production of sludge (SPS)	g TS_{out} g^{-1} VS_{in}	0.102
12	Production of excess sludge (TS = 4.5 %)	g d^{-1}	~ 68
13	Supernatant production	g d^{-1}	~ 55

4. Technological design of a biogas plant for the poultry farm

The technological design of the biogas plant was carried out based on the current characteristics of the poultry farm and the operational characteristics obtained in the experimental study, during best reactor performance. Personal experience and consultations with professionals were used in the estimation of the main components of the biogas plant. In table 4, the parameters of the biogas plant can be seen.

According to table 4, the main digester of the biogas plant should have a volume 3236 m^3. Based on practical experiences, two smaller digesters with a volume of 1800 m^3 are proposed. Additionally, a post-digester with enough volume to store the excess-sludge production of at least three months should be taken into account. Thus, a post-digester with a volume of 2000 m^3 is taken into account.

For the storage of chicken litter, an open horizontal silo with a volume of 600 m^3 is proposed. Similarly, a storage tank for the lipid source (waste kitchen oil) with a volume of 500 m^3 has been included in design of the biogas plant. The main objects of the biogas plant are illustrated in figure 2.



Main components of the biogas plant:
BS1 Digester 1, **BS2** Digester 2, **BS3** Post-digester, **BS4** Lipid storage tank, **BS5** Silo for chicken litter, **BS6** CHP Unit, **BS7** Biogas holder, **BS8** Centrifuge, **BS9** Sludge management area

Figure 2 Illustrative scheme of the biogas plant along the poultry farm.

Regarding biogas conversion into energy, a CHP unit with installed power of 500 kW is suggested based on the results from the laboratory study. Previous to combustion, biogas should be upgraded with a chemical scrubber, in order to remove hydrogen sulphide. Biogas should be stored in a biogas holder in order to provide a fully-homogenised and continuous volumetric flow to the CHP unit.

The electricity produced from combustion of biogas will be delivered to the public network. Based on the pricing policy specified by the Regulatory Office for Network Industries (ÚRSO, 2017), the current price for electricity produced from biogas in CHP units is 106.84 € MWh^{-1} (for CHP units smaller than 500 kW). The poultry farm pays about 85 € MWh^{-1} on average for electricity. Thus, with the subsidization policy for electricity, every MWh consumed by the poultry farm and the biogas plant will be generating a green bonus of 21.84 € (Table 7).

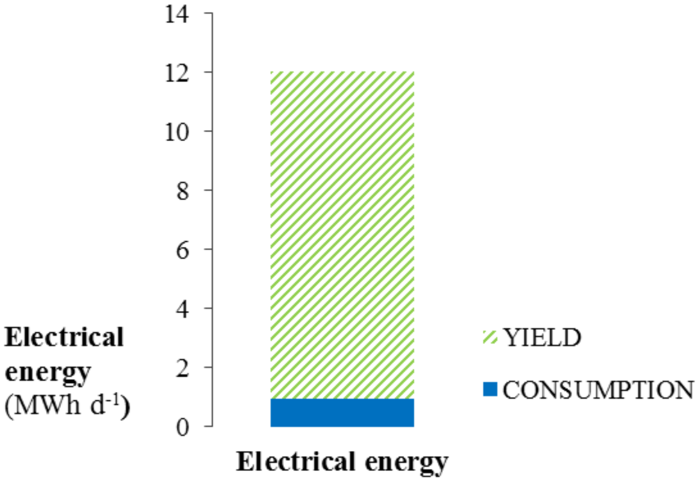


Figure 3 Yield of electrical energy by combustion of biogas in the CHP unit and consumption of electricity by the poultry farm and biogas plant

Daily electricity consumption of the poultry farm is about 450 kWh, according to table 1. Electricity consumption of the biogas plant is estimated at 500 kWh d^{-1} based on professional consultations. Consumption of electricity by the poultry farm and the biogas plant represents less than 8% of the total yield of electricity (Figure 3).

Table 4 Technological design of a biogas plant for the poultry farm

N	**Parameter**	**Abb.**	**Units**	**Value**
	Feedstock parameters			
1	Feeding rate	$M_{total,in}$	Mg d^{-1} or m^3 d^{-1}	21.6
2	Substrate feeding rate	$TS_{total,in}$	Mg d^{-1}	9.3
3	Organic matter feeding rate	$VS_{total,in}$	Mg VS d^{-1}	6.5
4	Chicken litter feeding rate	M_{litter}	Mg d^{-1}	6.0
5	Chicken litter feeding rate (VS)	VS_{litter}	Mg VS d^{-1}	3.2
6	Waste oil feeding rate	M_{GLY}	Mg d^{-1}	3.2
7	Waste oil feeding rate (VS)	VS_{GLY}	Mg VS d^{-1}	3.2
8	Fresh water input	M_{water}	Mg d^{-1}	12.3
	Operational parameters			
1	Organic loading rate	OLR	kg VS m^{-3}	2
2	Solid retention time	SRT	d	150
3	Volume of storage silo for chicken litter	V_{silo}	m^3	500
4	Volume of sludge	V_{sludge}	m^3	3236
5	Volume of main anaerobic reactor	$V_{reactor}$	m^3	3300
6	Volume of post-digester	$V_{digester}$	m^3	1500
	Output parameters			
1	Biogas production rate	Q_{biogas}	Nm^3 d^{-1}	4556
2	Methane production rate	Q_{CH4}	Nm^3 d^{-1}	2870
3	Electrical energy	E_{el}	kWh d^{-1}	12063
4	Thermal energy (heat)	E_{th}	kWh d^{-1}	18094
5	Engine power (CHP)	P_{CHP}	kW	500
6	Electricity sales income	I_{el}	€ d^{-1}	1303
7	Heat sales income	I_{th}	€ d^{-1}	633
8	Excess sludge production rate	$M_{total,out}$	Mg d^{-1}	14.7
9	Excess sludge production rate	$TS_{total,out}$	Mg TS d^{-1}	0.7
10	Total reduction of solid matter (TS_{in}/TS_{out})	$TS_{reduction}$	%	92
11	Supernatant production rate	$M_{supernatant}$	Mg d^{-1}	11.0
12	Nitrogen recovery potential (sludge)	N_{out}	kg N d^{-1}	19.1
13	Phosphorus recovery potential (sludge)	P_{out}	kg P d^{-1}	0.4
14	Sulphur recovery potential (biogas)	S_{out}	kg S d^{-1}	913.2

As for heating, figure 4 shows the average daily heat consumption of the poultry farm, based on real bills provided by the owner of the plant (Table 1). Every year, the poultry farm consumes about 319 200 Nm^3 (3 091 MWh). Furthermore, figure 5 shows the consumption of heat by the biogas plant for heating of the main digesters. It can be seen that temperature plays an important role on the final consumption. The walls of the digesters and the post-digester should be composed by layers of different materials with a thickness of 0.8 m for concrete, 0.1 m for polystyrene and 0.001 m for concrete. Therefore, for the estimation of the heat consumption of the biogas plant, heat transfer coefficients for concrete (1.194 W m^{-1} K^{-1}), polystyrene (0.05 W m^{-1} K^{-1}) and cement (1.047 W m^{-1} K^{-1}) were used.

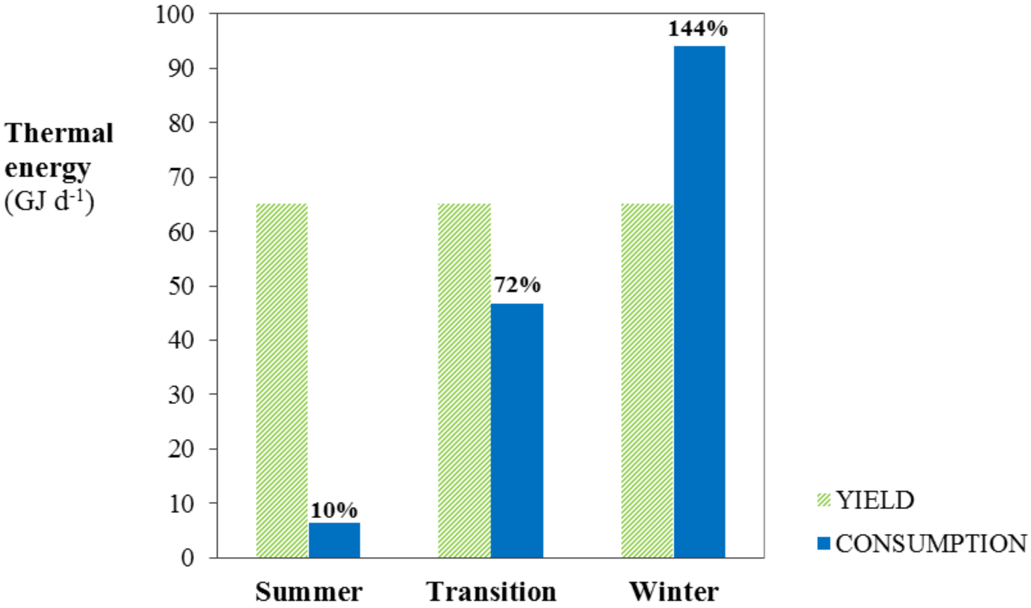


Figure 4 Production of heat by combustion of biogas in the CHP unit and average consumption of heat by the poultry farm and the biogas plant in different seasons of the year

The use of heat is an important issue in most biogas plants. During winter and transitional seasons, the surplus of heat can be sold to the public network at the tariff specified by ÚRSO (2017). However, in summer season, the use or sale of heat can be a complicated task. Many used of heat during summer season can be found in Germany and the Czech Republic, such as drying of straw, drying of excess sludge for its use as soil amender, production of vegetables in greenhouses, heating of swimming pools, among others.

Regarding excess sludge from the biogas plant, its use or sale as organic fertiliser or soil amender is possible under certain conditions. For instance, chemical analyses in a certified laboratory and on a regular basis could be necessary, in order to guarantee the quality and safeness of the organic products.

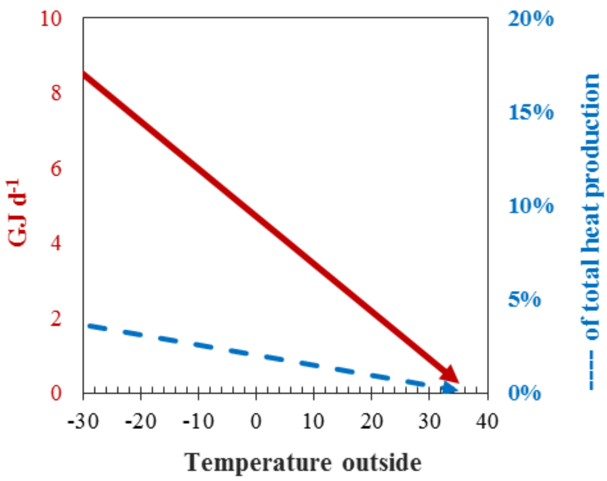


Figure 5 Self-consumption of heat by the biogas plant

5. Brief economic balance of the biogas plant

This section of the study offers illustrative information on the economic outlook of the biogas plant, based on the results of the laboratory study, professional consultations and current construction prices, wages, costs of energy and other media.

Regarding the cost of the biogas plant construction, a simplified summarisation from a bill of quantities (BOQ) is provided in table 5, based on personal experience and professional advice. Thus, an investment of about 1 500 000 € will be necessary.

Table 5 Simplified bill of quantities for the construction of a biogas plant

1	Building works	€	850 000
2	Technical equipment and software	€	600 000
3	Project, paperwork and others	€	50 000
	Total	**€**	**1 500 000**

In relation to operational costs, the wages for personnel were calculated on 187 200 € $year^{-1}$, considering that one engineer, one dealer, four operators and two other employees will be working full-time in the biogas plant. Furthermore, the maintenance costs of the plant were estimated to 10% of the investment costs, based on professional advice. Table 6 illustrates all specific costs used for the calculation of the operational costs.

Table 6 Specific cost of media and personnel in Slovakia (ÚRSO, 2017)

	Media		
1	Electrical energy	€ MWh^{-1}	85
2	Thermal energy	€ MWh^{-1}	36.2
3	Natural gas	€ Nm^{-3}	0.031
4	Calorific value of natural gas	MJ m^{-3}	9.684
5	Electrical energy produced from biogas ($P_{CHP} \leq 500kW$)	€ MWh^{-1}	106.84
6	Potable water	€ m^{-3}	0.9359
7	Wastewater treatment	€ m^{-3}	1.09
8	Waste kitchen oil (lipid source)	€ Mg^{-1}	24
9	Soil amender (TS > 25%)	€ Mg^{-1}	25
10	Organic fertiliser (TS ~ 4.5%)	€ Mg^{-1}	2.50
	Wages for personnel		
1	Engineer	€ $month^{-1}$	3000
2	Dealer	€ $month^{-1}$	3000
3	Operator	€ $month^{-1}$	1600
4	Other type of employee	€ $month^{-1}$	1600

Biogas projects are characterised by high specific costs. In many cases a single farmer or even a consortium of investors is not capable of financing the whole project by equity capital. Therefore, borrowed capital is essential for the implementation of a biogas plant. In the European Union, there are many different types of financing, such as banks, project financing, leasing, biogas contracting and investment funds. Each financing methods has advantages and disadvantages for each particular case (Rutz and Ferber, 2011). Therefore, in order to simplify the calculations, a loan of 1 500 000 € from a financial institute (bank) has been considered. In this manner, for an amortisation rate of 2.5 % (annual basis) and a payback length of 15 years, the annual amortisation for the biogas plant was estimated at 128 928 €, and it was included among the operational costs of the plant (Table 7).

Table 7 Summarisation of all operational costs from the biogas plant

Operational costs of the biogas plant			
1	Fresh water	€ $year^{-1}$	4 197
2	Wastewater	€ $year^{-1}$	4 377
3	Lipid source (waste oil)	€ $year^{-1}$	29 526
4	Wages of personnel	€ $year^{-1}$	187 200
5	Amortisation	€ $year^{-1}$	128 928
6	Maintenance of the biogas plant	€ $year^{-1}$	150 000
7	Heat needs of the poultry farm in winter that cannot be covered by the biogas plant	€ $year^{-1}$	23 091
	Total	**€ $year^{-1}$**	**527 319**
Savings for the chicken farm			
1	Electricity	€ $year^{-1}$	9 639
2	Heat	€ $year^{-1}$	88 808
	Total	**€ $year^{-1}$**	**98 447**
Income from sales			
1	Sales of electricity to public network	€ $year^{-1}$	433 361
2	*Green energy bonus	€ $year^{-1}$	2 477
3	Sales of heat to public network	€ $year^{-1}$	93 244
4	Soil amender (TS = 25%)	€ $year^{-1}$	10 842
	Total	**€ $year^{-1}$**	**552 409**
	TOTAL ECONOMIC BALANCE	**€ $year^{-1}$**	**+ 123 537**

There are many possible economic optimisations that can be gradually implemented, such the recovery of nutrients from the supernatant (N, P, K) and biogas (S). A second one, could be the substitution of waste kitchen oil by a cheaper lipid source (from the food industry for instance) which may even generate an extra income. Another optimisation could be on the consumption of potable water by the biogas plant and its subsequent production of excess sludge, by enhancing supernatant recirculation.

A priority task for the owner of the biogas plant is the further tuning and optimisation of the economic balance of the biogas plant. The cooperation between the biogas plant and research centres or universities is of vital importance for the optimisation of reactor performance, the inclusion and testing of new substrates and the development and implementation of new technologies.

6. Conclusions

In the current operational scheme, the poultry farm spends on average about 121 538 € $year^{-1}$ on energy, comprised of 9 639 € for electricity (113.4 MWh) and 111 899 € for natural gas (319 200 Nm^3). Moreover, the waste management of about 2160 Mg $year^{-1}$ of manure is carried out by an external partner and consequently, it could generate significant costs on transportation and disposal.

Within the concept of SMART-FARMS, the proposed biogas plant would be able to cover all the expenses on energy needs of the poultry farm. Through anaerobic co-digestion, it would provide a reliable source of energy based on the amount of manure produced in the farm itself. Therefore, it optimises the waste management of the farm. Furthermore, the biogas plant would generate a surplus of 123 537 € $year^{-1}$ for the poultry farm and contribute to the generation of 8 new local jobs.

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