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Norwegian Small Scale Biogas Plant: Estimations on Energy Use, CO_2 Emissions-Reduction and Added Value

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Research Article

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ABSTRACT

An anaerobic digestion (AD) process is studied. The AD reactor belongs to UASB (up-flow anaerobic sludge blanket) typology and it was constructed in a typical Norwegian farm (Foss farm) localized in Skien, Norway. The reactor is fed with cattle manure. The process is divided into two different parts: pre-treatment and AD, nitrification and post-treatment. Biogas and compost are outputs of the first section, liquid fertilizer output of the second one. This paper has two core parts: energy/mass flows determination and CO_2 emissions-reduction assessment. The study has indicated that energetic consumption is bigger than production. Radiation losses represent the most important terms of consumed energy, but is possible to diminish them by changing insulation and/or reactor shape. The pilot plant has an average energy consumption and thermal production of 1592 kWh/year and 482 kWh/year, respectively. The equivalent CO_2 emissions of open-air-standing cow's manure are noteworthy. Two different probable situations are analyzed: processed manure and not processed manure. The reduction of carbon dioxide releases in the first case, compared to the second, is significant and goes from 32% to 83%. It could be possible to reduce energetic consumption up to 18% halving radiation losses and raise energetic production up to 250% by increasing the methane yield from 20% to 50% of the maximum value.

INTRODUCTION

Anaerobic digestion (AD) is a green-house gases (GHG) saving tool and a renewable energy carrier [1]. This work focuses on a small-scale biogas plant built in Foss farm in Skien, Norway. The substrate is cow's manure. The process is divided into AD, in an UASB (up-flow anaerobic sludge blanket) reactor typology, and nitrification. The latter allows achieving high nutrient's level in the output fertilizer [2]. The input of the process is the manure (with 25% of added water), while the output are biogas from AD, compost from the initial separation and the final fertilizer after the nitrification (solid and liquid part). The present reactor in FossLab has been in operation since April 2012. Main goals of this work are to evaluate the energetic flows (production and consumption) and to demonstrate that processing manure means less $CO_{2,equ}$ emissions.

MATERIALS AND METHODS

Process description

The initial substrate's flow is 60 L/day. It is pumped (P1) from the reservoir open-air tank (R) to a buffer tank (B). Later, it is mixed (M1) and sieved (S) separating 30% of solid (vermi-composting) and 70% of liquid. The latter is pumped (P2) in the AD reactor (AD). This UASB AD reactor has kept at an average value of 32°C (operational range 25°C / 35°C). Average biogas production is 230 L/day containing 70% of CH_4. The AD effluent has sent to the nitrification reactor (N) in which ammonia is converted into nitrate thanks to oxygen [3], entering in reaction through the air pumped in (P4). Nitrified effluent is mixed (M2) and separated in two different stages: a funnel-shaped tank, in which half of the influent is removed as solid and half, as liquid, is pumped (P3) in an oozing bag. Here 70% of the total is the filtrate-part and the rest part is solid-foam. Output of the overall process will be biogas and fertilizers (the vermin-composting in the first stage, the liquid and solid fertilizers after the nitrification). In the next table are summarized all components data **(Table 1).**

Table 1. Data of reservoir open-air tank (R), pumped (P1), buffer tank (B), mixed (M1), sieved (S), pumped (P2), reactor (AD), pumped in (P4), nitrification reactor (N), mixed (M2), pumped (P3).

	R	P1	B	M1	S	P2	AD	P4	N	M2	P3
Volume [L]	2500	/	400	/	/		250	/	200	/	/
Entering flow [L/day]	60	/	/	/	/	42.5	/	/	41	/	/
Capacity [kW]	/	1.1	/	0.75	3	0.4	/	0.4	/	0.4	0.55

Data collection

For the following work were used: online data monitored through sensors-network 8 times per hour (Data 1), offline data hand-measured through sample-survey about twice a week (Data 2), data measured in the lab (Data 3) and data taken from literature (Data 4). The first two types are present in a database implemented for a previous work [2] in the same lab, starting from 19th April 2012 and ending on 20th February 2014. Below all data are summarized **(Table 2).**

Table 2. Online data monitored through sensors-network 8 times per hour (Data 1), offline data hand-measured through sample-survey about twice a week (Data 2), data measured in the lab (Data 3) and data taken from literature (Data 4).

Data 1	Data 2	Data 3	Data 4
Biogas flow [L/d]	COD in substrate [gCOD/Lfeed]	Pumps capacities [W], working time [h] and dimensions [m]	(4) Calorific value of methane [MJ/Nm3]
Methane concentration [%]	VS in substrate [gVS/Lfeed]	Mixers capacities [W] , working time [h] and dimensions [m]	(5), (6) Substrate heat capacity and density [kJ/kg/K]
CO2 concentration [%]	TS in substrate [gTS/Lfeed]	Sieve capacity [W] , working time [h] and dimension [m]	(7), (8), (9) Steel, insulation and ground thermal conductivities [W/m/K]
Feeding AD flow [L/d]	/	Lamps capacities [W] and working time [h]	(10) Air heat transfer coefficients [W/m2/K]
Inlet AD reactor temperature [°C]	/	AD reactor dimension [m]	Thermal and electricity energy efficiency [%]
Room temperature [°C]	/	Nitrification reactor dimension [m]	(11) Sensors and computer capacities [W]
Reservoir tank temperature [°C]	/	Reservoir and buffer tank dimensions [m]	/

Energetic balance

In order to understand if this lab is energetically free-standing an energy balance was implemented. The net energy was calculated according to (1).

$$\mathbf{E} = \mathbf{E}_{\mathbf{produced}} - \mathbf{E}_{\mathbf{losses}} - \mathbf{E}_{\mathbf{consumed}} \tag{1}$$

Two producing cases were taken in account: thermic or electrical energy produced. Assuming respectively 60% efficiency (gas/steam turbine combined cycle) and 30% efficiency (advanced gas-turbine engine). These equations terms are evaluated in the appendix according to (2) and (3).

In the histogram **(Figure 1)** above it is possible observe many terms: the three red producing-energy-terms need to be considered originating from the zero-value-ordinate with the last one which represent the energy produced with the biogas with a 100% efficiency. The consuming-energy-terms are cumulative with the radiation losses, represented in a lighter blue to highlight their variation with the outlet temperature. Reactor temperature and feed flow are present too to clarify the seasonal energy flow variations.

Energy losses are divided into radiation losses (4) of the AD reactor, because the inlet reactor temperature is always above the room temperature, and heat needed for the substrate (8), to bring the substrate from the outlet temperature to above 30°C for the biological process.

Energy consumed in FossLab is due to the pumps (P1, P2, P3 and P4), to the sieve, to the mixers (M1 and M2), to the lightning system (one LED lamp) and to the controlling system (sensors and computer). It was calculated using the maximum power capacity and the working time of each component according to (9), (10), (11), (12) and (13) respectively.

CO_2 emissions

Two different cases were taken in account: processed manure (Case 1) and not processed manure (Case 2). In the first case the emissions would be due to the CH_4 reacting in the combustion (Case 1.1), to the CO_2 present in biogas and no reacting in combustion (Case 1.2) and to the CO_2 resulting by the production of energy consumed in the lab – assuming it is produced by natural gas (Case 1.3). In the second case, emissions would be due to the outside standing manure producing CH_4 (Case 2.1) and to the emission of CO_2 resulting by the production of energy of the previous case (Case 2.2).

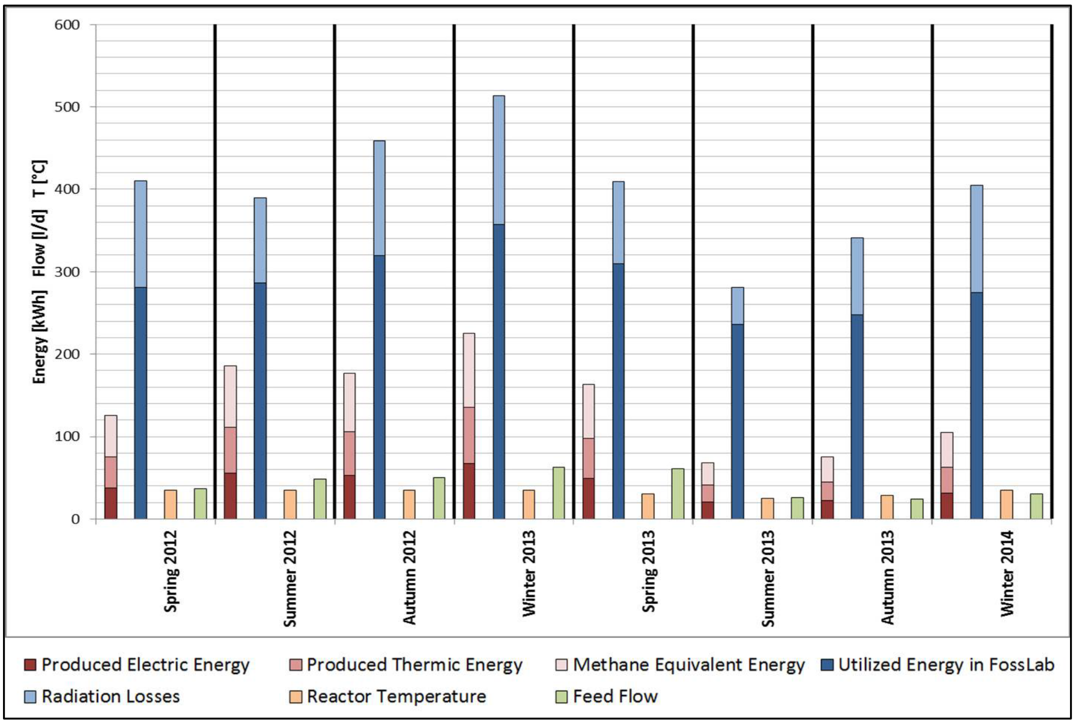

Figure 1. Seasonal Energy flows.

Have been used three different values of methane produced by cow's manure from literature [4-6] in order to achieve an objective benchmark action figured above **(Figure 2).**

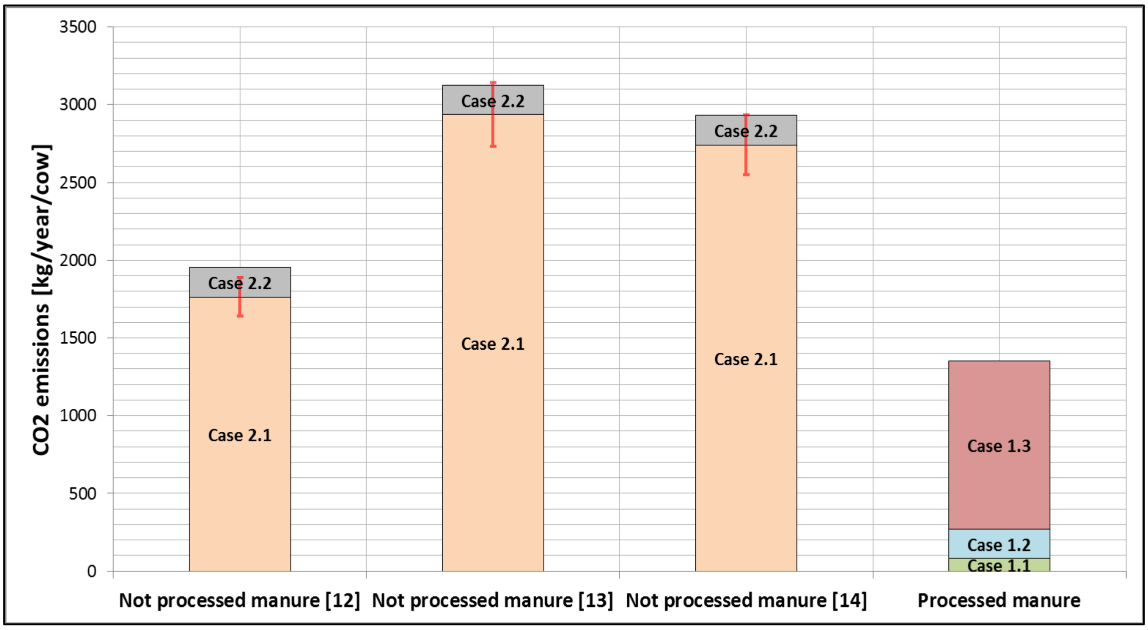

Figure 2. Carbon dioxide emissions.

RESULTS AND DISCUSSION

Mass flow analysis was implemented using COD, VS and TS concentration [g/L_{feed}] database-values in order to determinate the biological efficiency represented by the yield [L_{CH4}/g] calculated by (14) and (15). Stoichiometric value of the latter yield is 0.35 L_{CH4}/g_{COD} according to (17). Fixing the COD yield (15) with values equal to 50%, 75% and 100% of the stoichiometric one, were evaluated biological efficiencies (14). If the latter increase, the produced energy will grow as well. Results are tabled below with mean values for the yields and summed (during database period) values for energy **(Table 3).**

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Table 3. Mass flow otpimization.

Case	COD yield	Yield percentage	VS yield	Electric energy	Thermic energy	Methane equivalent energy	Energy percentage
	[L CH4 / g COD]	[%]	[L CH4 / g VS]	[kWh]	[kWh]	[kWh]	[%]
1	0.0713	20	0.126	337.4	674.8	1124.7	/
2	0.175	50	0.311	841.1	1682.3	2803.8	149%
3	0.2625	75	0.466	1261.7	2523.4	4205.7	274%
4	0.35	100	0.621	1682.3	3364.6	5607.6	398%

Another analysis has been realized, studying radiation losses. In the real case (Case A), radiation losses represent 28% of consumed energy (4). This term was reduced by several procedures:

- changing AD reactor shape minimizing surface's area in contact with the room temperature (Case B),
- decreasing the insulation's thermal conductivity from 0.06 W/m/K to 0.04 W/m/K [7] (Case C),
- increasing insulation's thickness from 5 cm to 8 cm (Case D),
- considering the best case as a 'sum' of all previous cases (Case E).

Results are summarized following **(Table 4).** In the case E radiation losses characterize 12% of the overall consumption.

Table 4. Energy flow optimization.

		Mean radiation losses [kWh/d]	Percentage in respect to real case [%]	Mean total consumed energy [kWh/d]	Percentage in respect to real case [%]
Case A	Real case	1.23	/	4.36	/
Case B	Changing reactor shape	0.88	-28%	4.02	-8%
Case C	Decreasing insulation thermal conductivity	0.85	-30%	3.99	-9%
Case D	Increasing insulation thickness	0.81	-34%	3.94	-10%
Case E	Best case	0.44	-64%	3.57	-18%

CONCLUSION

The AD process in FossLab consumes more energy than it produces. This gap may be reduced through some expedients in order to increase the energy production such as increasing the COD yield (and the biological efficiency) or some procedures in order to decrease the energy consumption (radiation losses). On the other hand, this technological process reveals itself to be one of the best ways to avoid outstanding cattle manure emissions of CH_4, which is a strong GHG [5] and influences the global warming.

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