Tehno-economic optimization of a biogas-cogeneration plant for energy demands of a livestock farm

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Abstract: *In this paper, energetic and financial annual balance of a livestock farm is performed. The results of the balance are used to determine current energy costs at the farm, properties of its energy demands, as well as potentials for on-site production of biogas. Dynamic annual performance model of the farm is created using TRNSYS software, and used for Genopt optimization of the farms energy supply. A generic model of a biogas fired cogeneration system based on an internal combustion engine and heat storage tank system is created to determine economic benefits of cogeneration. Investment costs are calculated as function of engine power and heat storage volume. Power of the cogeneration system and volume of its heat storage are optimization variables. The goal function is based on net present value, where energy savings and cash flows are affected by the simulated annual performance of the cogeneration system. Results of optimization obtained using Trnsys-Genopt with two different optimization algorithms are presented and discussed in the paper.*

Key words: *Biogas cogeneration, optimization, net present value, energy savings, farm biogas production*

INTRODUCTION

Production of biogas on livestock farms is recognized as a measure for improved waste management and energy supply improvement in the literature [1-10]. A recent research indicated that agricultural production is the hot spot of life cycle of food products, where impact of waste management systems in pig farming and environment impact are analyzed, but energy supply systems are omitted from the research [1]. Multiple environmental benefits in different sectors have been recognized from the Danish farm experience with centralized biogas plants from the 1970s until now: it generates renewable energy, it enables the recycling of organic waste, it can play a role in manure distribution and storage and improve the veterinary aspects of manure, it can reduce fertilizer use, and it contributes to the reduction of the greenhouse gas methane [2]. The composition of input substrate affects methane and biogas yield, and can be further used to produced heat, steam and electricity [3]. In an economical analysis of available biogas production technologies in Sweden and utilization of biogas for production of heat, combined heat and electricity (CHP) and vehicle fuel, CHP option showed favorable economic feasibility, but also highest sensitivity to the tested parameters [4]. Comparison of eight waste to energy technologies in today's energy systems showed that utilization of organic waste in manure based biogas production provides cheaper CO_2 reduction than incineration, and utilization of biogas for CHP provides the lowest CO_2 reduction cost [5].

In this paper, possibilities for biogas cogeneration are analyzed through a case study of an intensive pig farm. Energy performance data of the farm are collected and used to determine potential for on-site biogas production. The data is used to model energy demands of the farm, and a biogas fired cogeneration system in Trnsys software. Techno-economic Trnsys/Genopt optimization is performed to determine optimal size of the internal combustion engine biogas cogeneration plant.

ENERGY DEMANDS OF THE FARM

Energy consumption at the farm is represented by heating and electricity demands. Electricity consumption data was collected for a period of 3 years, and average monthly values are presented in Fig. 1. Heat is supplied by two 750kW boilers, to animal housing buildings, an office building and sanitary hot water system. Mass flow rates and temperatures of water supply and return, and water supply to the animal housing and office buildings were measured using Greyline PT400 mass flow rate sensor and TESTO 831 temperature sensor. Temperature of the main supply pipeline was read from an existing thermometer in the boiler house. The following temperatures were read at the time of the measurement (Fig 1): main supply pipeline temperature 90°C, temperature at inlet for heating buildings 81.2°C, temperature at office building inlet and SHW heating 74.5°C, temperature at main return pipeline 71.6°C .

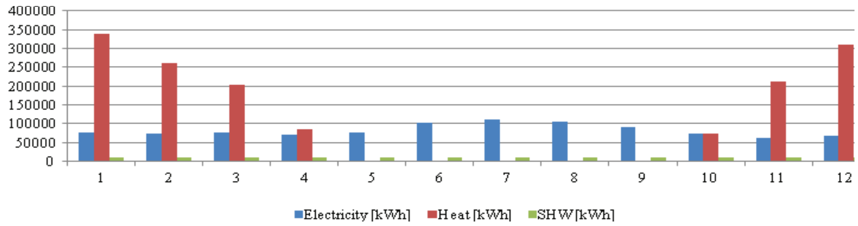

Fig. 1. Annual energy demands at the farm

Total heat consumption of the system, together with the distribution losses was found equivalent to 2270MWh. Specific energy consumption per animal head was calculated and compared to the benchmark values [6]. Results are presented in Table 1.Breakdown of the farms energy supply costs is presented with respect to the following assumptions: (1) Cost of kWh of supplied heating is calculated based on annual coal consumption for 4320 hours of the heating season, fuel cost [12] in €; and (2) Cost of electricity is taken from the available data, as average cost per kWh. With these assumptions, the cost of heat supply is 10.125€/MWh and the average cost of electricity is 61.97€/MWh.

TABLE 1 Calculated energy indicators compared to benchmark values

Indicator	**Unit**	**Value**	**Benchmark value**
Water consumption	m^3/head/year	1.19	1.825 (partly slated floor) 0.07-0.3 (Breeding and finishing farms)
Electricity consumption	kWh/head/year	43.43	42.7 (Integrated farms)
Thermal energy consumption	kWh/head/year	49.28	43.74 (Integrated farms)
Total energy consumption	kWh/head/year	92.72	83-124 (over 450 sows/year) 41-147 (over 2100 piglets/year)

BIOGAS BASED COGENERATION (BCHP)

Generally, quantities of manure, sludge and urine generation are difficult to measure, and therefore they were estimated according to daily values [6] per animal and average livestock count for the farm. Possible methane production was calculated using average values for methane yield from the literature [7]. Biogas potential was calculated based on the theoretical amounts of biogas produced per unit of fresh pig slurry a produced slurry calculated for the average type and number of animals at the farm [7,8].

Table 2 Estimated organic waste for biogas production

		***Heads* No.**	***Slurry* (kg/head/day)**	***Solid manure* (kg/head/day)**	***Urine* (kg/head/day)**
Finishers		7870	5.35	3	1.5
Weeners		5221	1.85	1	0.5
Finishers (160 kg)		2	11.5	6	10
Farrowing sows		1080	13.4	5.7	10.2
Gestating sows		258	7.1	2.4	4.7
Suckers		3104	1.85	1	0.5
Gilts		258	3.6	2	1.6
Total	**(kg/day)**		**17535**	**39238.2**	**28628.9**
	(m3/day)		**16.86**	**37.729**	**28.628**

Available slurry for methane production is estimated to 74.6 t per day (Tab 2), and a biogas yield of 27.5 m^3 of biogas per *t* of fresh slurry [9], annual methane yield is estimated to 450242.1 m^3. For this estimation, a ratio of methane in produced biogas of 60% is assumed [10]. An economic analysis of available biogas production and utilization in Sweden rated combined production of heat and electricity (CHP) as a favourable biogas utilization technology [4]. According to estimated annual methane production capacity, a CHP unit could be used to cover base heating loads and produce electricity. In order to obtain a valid permit for selling electricity, average annual efficiency of 85% for the cogeneration unit has to be insured [11]. Project profitability is obtained if the CHP module is operated throughout a year with utilization/sale of both heat and electricity produced. For solid fertilizer production, heat is applied to dry the digestate, a byproduct of the biogas production used for fertilizer production. For the CHP produced electricity, an export price of 123.1€/MWh_e [12] was accounted for. According to literature review [13,14], investment cost for the biogas CHP plant I_{BCHP} is estimated according to installed power for electricity production of the CHP P_{CHPe} module as:

$$I_{BCHP} = -1.09 P_{CHPe} + 3602 \quad (1)$$

Optimization of a BCHP plant

Based on the results of the preliminary analysis, the estimated project costs and profits, and available raw material for biogas production, a dynamic annual performance model of the farms energy demands is created and couplet with the BCHP model in Trnsys software. The modelled BCHP plant exports electricity directly to the grid, while waste heat for the engines jacket water and flue gas heats a heat storage tank, which is further used for heating animal housing buildings. The system is equipped with a gas fired boiler, which is engaged when available heat from the heat storage is insufficient for maintaining room temperature above 16 ^{o}C.The performance of the modeled ICE with change of its part load ratio (PLR) is given in table 2.

Table 2. Part load ratio performance data of the simulated ICE (fraction of nominal value)

Part Load Ratio	Mech. Eff.	Elect. Eff.	Waste Heat to Jacket Water	Waste Heat to Oil Cooler	Waste Heat to Exhaust	Waste Heat to Aftercooler	Waste Heat to Environment
0.4	0.338	0.921	0.311	0.07	0.532	0	0.087
0.5	0.35	0.932	0.314	0.071	0.526	0.013	0.076
0.6	0.359	0.936	0.314	0.071	0.521	0.026	0.068
0.7	0.365	0.939	0.314	0.07	0.517	0.037	0.061
0.75	0.367	0.939	0.313	0.07	0.515	0.043	0.059
0.8	0.368	0.939	0.313	0.07	0.513	0.048	0.056
0.9	0.368	0.939	0.31	0.069	0.512	0.057	0.052
1	0.364	0.939	0.307	0.068	0.514	0.065	0.047

Net annual savings achievable by application of BCHP at the analysed farm are calculated with assumptions: 1) all of the available organic waste at the farm is used for biogas production and available for use by the engine, 2) Cost of the used biogas is negligible small, 3) Natural gas is used when biogas consumption of the ICE exceeds biogas consumption, 4) Natural gas fired boiler is used when the ICE generated heat is insufficient for achieving desired indoor temperatures. The following parameters were calculated to investigate financial and economic feasibility of the project [15]: Net annual savings:

$$B = \sum B_t P_e - \Delta C_e \quad (3)$$

Where: *B*-total annual savings; B_t – energy savings for one year (t=1…n); ΔC_e - exploitation cost change. Net present value NPV:

$$NPV = \sum_{0}^{n} B_t / \left(1 + d^t\right) \quad (4)$$

Where: *d* – discount rate; *n* – estimated project lifetime, *B* – annual net cash flow (revenue).

Simulated BCHP performance in interaction with the simulated energy demand performance in each time step for a typical meteorological year. The presented economic parameters strongly depend on the simulated fuel consumption and fuel costs. Initial cost of the ICE cogeneration module is determined as per eq. (1), whereas heat storage tank cost is assumed as an average cost of 400 EUR/m^3 of tank volume. TRNSYS/Genopt optimizations were conducted using negative value of NPV as optimization goal function, where the minimum of the negative value of NPV for 12 years of the project, in the given domain is the optimal point.

RESULTS AND DISCUSSION

For the created model of energy demand and BCHP plant based on an ICE engine with performance described in table 2, Genopt opimizations were conducted to determine the optimal size of the BCHP plant, i.e. the optimal power of the ICE and the optimal volume of the heat storage tank. Energy and fuel costs are considered constant. A discount rate of 5% was used in economic evaluation. General Patern Search –Coordinate Search (GPS-CS) Algorytm (Fig. 2.a), as well as Hook Jeeves algorhytm were used for optimization (Fig 2.b). Both of the used algorhytms showed convergence and pinpointed the solution. A BCHP plant of 500 kW with 100 m^3 of heat storage is the optimal solution is obtained using Hook Jeeves algorhytm, after 40 iterations. The GPS-CS algorytm showed better precision, with a result of the minimum point found 499 kW, and 99.68 m^3, after 56 iterations, i.e. 56 simulation runs.

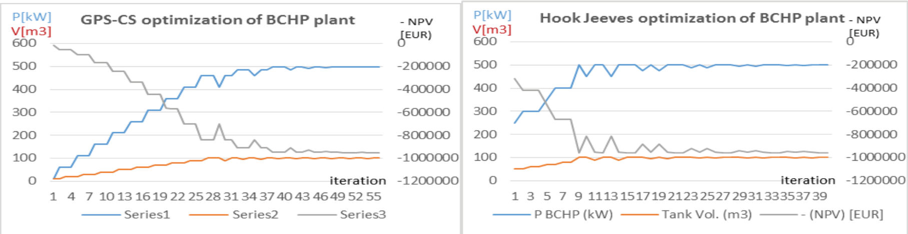

Fig. 2. a) GPS-CS optimization of the BCHP plant; b). Hook Jeeves optimization of the BCHP plant

CONCLUSION

In this paper, possibilities for utilization of BCHP on livestock farms were analysed on a case study of an integrated pig farm. A dynamic energy demand model of the farm was created using Trnsys software. Based on the annual dynamic energy demand model, with respect to meteonorm weather data, a BCHP system was modelled in Trnsys software to investigate its performance with the given energy demands. Trnsys/Genopt optimizations were conducted with the goal of finding optimal Power of the BCHP module and optimal volume of the coupling heat storage. Two methods showed similar results of the optimal point. Hook Jeves algorhytm showed faster convergence, while the GPS-CS gave more precision.

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