ANALYSIS OF INPUT BIOMASS PARAMETER IMPACT ON ELECTRIC CAPACITY FACTOR OF BIOGAS PLANTS

Lauris Plume, Imants Plume
Latvia University of Life Sciences and Technologies, Latvia
plume.lauris@gmail.com, imants.plume@lbtu.lv

Abstract. Factor of utilisation of electric power or electric capacity factor (CF) is low in agricultural biogas plants in Latvia due to low input biomass quality and/or biogas plants management practices. Different parameters of the silage in input biomass and in digestate output were analysed using statistical methods for 15 agricultural biogas plants in Latvia. Samples of silage were obtained from operating biogas plants and were analysed in certified laboratory. Multivariate statistical modelling of the factors was carried out to find determinants of the CF. Results of modelling showed that most important factors influencing CF value was ash percentage in silage (ASH) and proportion of silage (SIL) in input biomass of biogas plants explaining 34.7% of the variations in CF of the biogas plants with maximum probability 92.2 %.The comparison of two subgroups of biogas plants differing in total solids (TS) content in input silage with the first subgroup including biogas plants with silage TS content higher than 29.9 % and the second subgroup with silage TS content below 29.9 %, showed significant differences in mean CF values 0.812 or 0.645 (difference 20.6 %) in first or second subgroups, respectively, with probability above 95 %. Recommendations are to maintain the TS content of silage above 29.9 % and to reduce biodegradation of silage during storage, for example by covering silage heaps with oxygen-proof plastic film and reducing the opening time of heaps during removal of silage.

Keywords: anaerobic fermentation, biogas, methane, energy efficiency, silage.

Introduction

Biogas production in plants using agricultural biomass is considered as an environmentally friendly method for producing of energy and organic fertiliser. However, the number of agricultural biogas plants decreased from 50 in 2017 to 41 in 2022 in Latvia due to the reduction of state aid and/or the low energy efficiency of plants. To assess the energy efficiency part of agricultural CHP biogas plants were inspected, and samples of raw materials and fermentation residues (digestate) were analysed in a certified laboratory for nutrients content and pH value. In the surveyed biogas plants, the average input biomass consists of silage (31 %), various types of manure (58 %), food industry residues (8 %), and sewage sludge 3 %. Silage effluents have been observed in some biogas plants, which can be a potential threat not only to the environment but also to the efficiency of the biogas plants [1].

Various studies examine the problems of biogas plants and propose different solutions to improve the energy efficiency. Problems occurred in a small agricultural biogas plant (37 kW) fed with sheep manure, horse manure and grass-clover silage were evaluated using four technological scenarios and was concluded that the main possible improvements should be provided in feedstock and anaerobic digestion technology [2].

For on-farm biogas plant economic viability, the cost prediction and probability analysis before the start of its construction were evaluated by help of six regression models to assist the project developers. The models estimated the capital cost for farms with less and more than 1000 cows. Since there are minimum costs needed for running of the plant, it was concluded, that less than 300 cows on a farm will not produce a sufficient quantity of manure for the system's input. They will generate less electricity that may not be adequate even for maintaining the digester temperature at the optimum level in the weather conditions in Canada [3]. During biogas plant operation, a sufficient mixing of the organic mass in fermenter needed to ensure high biogas yields by bacteria and enzymes. Measurements of the electric power consumption of biogas plants revealed that the electrical energy demand of the stirrer system has a high share in the total electricity self-consumption of a biogas plant [4]. The performance of three biogas plants with side mechanical rod stirrers; side 4 sprinkling nozzles, and with side-rod stirrers and immersible stirrer with a comparable installed electrical power 600 kW show, that best capacity factor 0.98 and low self-consumption of electricity 6.7 % have a biogas plant with fermenter stirred by four sprinkling nozzles placed in the upper part of the tank. Using a nozzle mixing and circulation system to heat the substrate eliminates the need for mixers or heat exchangers in the tank [5].

Suitable raw material choice is crucial for environmental and economic viability of biogas plants. Using the multi-criteria analysis TOPSIS methodology and considering the economic feasibility, substrate efficiency, and environmental aspects show that pig manure is the most suitable raw material for biogas production in Latvia, while poultry manure was ranked second. Lignocellulose rich straw was the third best substrate for biogas production followed by cattle manure, maize, and wood biomass [6]. Other research [7] shows that the best work efficiency can be achieved by agricultural biogas plants using co-digestion of silage, manure, apple pomace, potato pulp (biogas plant No. 1), followed by biogas plant No. 3 with co-digestion of sewage sludge, flotate, feathers, and biogas plant No. 2 has the lowest efficiency, which uses stabilized sewage sludge. Dry matter content of the substrates and dry organic matter content significantly influence the efficiency.

Evaluation of 31 farm-scale biogas production facilities in Sweden was provided by Ahlberg-Eliasson et al. (2016) and identified parameters of importance for further positive development. Plant operation data, biogas yield and data on digestate quality for 27 biogas plants were statistically analysed and was concluded that energy obtainable in biogas plants strongly depends on the degradation level of feedstock biomass [8].

Investigation of 21 biogas plants shows that the feedstock characteristics have the largest impact on the degradation time. It was found that standard values of the methane yield are a helpful tool for evaluating the degradation efficiency. Adapting HRT to the input materials is the key factor for efficient degradation in biogas plants. No influence of digester series configuration to VS degradation was found. The mean VS degradation rate in the total reactor systems was 78 ± 7% [9].

The EU legislation will provide restrictions on the share of energy crops in biogas production, so there is of interest to compare biogas plants with a different proportion of silage in the biogas feedstock. Environmental impact for two agricultural biogas plants with share of silage 59.4 % (plant A) and 11.2 % (plant B) was analysed using Life Cycle Assessment (LCA) methodology. The LCA analysis indicated that a biogas plant A with a lower level of waste heat utilisation and with substrates delivered by wheeled transport has a negative impact on the environment. Biogas plant B is an example of good organisation of the waste-to-energy process by transporting of substrates via transmission pipeline and heat sales to the external customer [10].

The biological processes that are ongoing in the mesophilic anaerobic digestion (AD) of feeds to produce biogas have much in common with ruminant microbial digestion. Major difference is that ruminants up- or down-regulate their intake of feed depending on an array of feed (also animal, management, environmental) characteristics whereas the operator of an AD reactor ignores these traits and pre-programmes the daily input of feed [11].

A comparable situation can also be observed in Latvian agricultural biogas stations, where daily dose (receipt) of silage in feedstock does not change for long periods, without operator's care on changing of real parameters of feedstock, e.g. the silage quality. To maintain the energy efficiency of biogas plants using crop silage as feedstock, as many factors as possible should be considered, including the quality and quantity of silage used.

The aim of this research is to evaluate, with the help of statistical analyses, the influence of input silage and output digestate (pH value) parameters on the capacity factor of agricultural biogas plants operating in Latvia. Another purpose of research is to find out whether there is a statistically reliable difference in mean values of the parameters, including the capacity factor, silage parameters and digestate pH value between two subgroups of biogas plants, one of which includes plants that provide silage with a high dry matter content that prevents silage effluent run-off from silage heaps during storage, and the other group which includes biogas plants using silage with low dry matter that constitutes a potential risk of leakages from the silage storages.

Materials and methods

Data from the previous research for silage and digestate chemical parameters obtained for 15 biogas plants having silage share 11% to 100% in feedstock of biogas plants were included in this research. Most silages (92.5%) were produced from maize and only few biogas plants have small share of grasses silage. Silage preparation includes harvesting of energy crops in late summer or autumn in year 2020 and ensilaging in high heaps covered with plastic film to provide air-tight conditions.

Biomass sample analyses were provided in March 2021 and the results of the analyses were used for estimation of silage influence on the capacity factor of biogas plants in 3-months period (from January to March 2021) that best matches the period of utilization of silage. To simplify the estimation, it was assumed that the recipe of biomasses in feedstock of the biogas plant was not changed during the mentioned 3-months period.

The biogas plant electric capacity factor (CF) for the period was calculated as follows:

$$CF = \frac{Er}{P * h} \quad (1)$$

where, *CF* – electric capacity factor of biogas plant; Er – electricity supplied from the biogas plant to the network by the cogeneration equipment during the period, kWh; P – rated electric power of the cogeneration unit (CPH), kW; h – number of hours in the period.

Data on installed electric power and electricity supplied from the biogas plant to the network was obtained from State Construction Control Bureau of Latvia [12].

Statistical parameters, including correlation coefficients, multiple linear regression coefficients and means difference between groups of biogas plants were calculated using standard MS Excel statistical tools [13].

Results and discussion

15 biogas plants with the silage proportion from 0.11 to 1.00 in feedstock were selected to assess the influence of silage and digestate parameters on the biogas plant capacity factor. Other parts of biomass feedstock in biogas plants includes various types of manure, food industry residues and sewage sludge. Data on the capacity factor (*CF*), ash percentage in silage (*ASH*), proportion of silage in raw material (*SIL*), proportion of total solids (*TS*) and total organic solids (*TOS*) in silage and digestate pH are shown in Table 1.

Table 1

Silage and digestate parameters and capacity factor in biogas plants

Biogas Plant No	***CF***	***ASH*, %**	***SIL***	***TS***	***TOS***	**pH**
1	0.581	1.55	0.196	0.388	0.373	8.13
2	0.760	1.50	0.360	0.377	0.362	8.29
3	0.914	1.40	0.646	0.353	0.339	7.86
4	0.883	1.20	0.126	0.342	0.330	8.20
5	0.908	1.10	1.000	0.322	0.311	8.20
6	0.744	1.30	0.357	0.319	0.306	8.51
7	0.856	1.20	0.967	0.305	0.293	8.06
8	0.849	0.60	0.559	0.299	0.293	7.46
9	0.490	1.50	0.104	0.296	0.281	8.18
10	0.576	1.20	0.642	0.289	0.277	8.28
11	0.483	2.60	0.264	0.287	0.261	8.15
12	0.872	1.20	0.435	0.286	0.274	9.05
13	0.802	2.20	0.426	0.273	0.251	8.50
14	0.523	1.70	0.226	0.252	0.235	8.30
15	0.767	2.60	0.343	0.228	0.202	8.26
Average	0.734	1.523	0.443	0.308	0.293	8.229
Std	0.159	0.556	0.275	0.044	0.046	0.340

As it can be seen from Table 1, the average capacity factor for this group of agricultural biogas plants is 0.734. This value is much lower compared to the average capacity factor 0.911 calculated for 850 small German agricultural biogas plants in year 2018 [14].

A variance analysis of all factors was performed using the MS Excel data analysis tool Dispersion. As a result of the data analysis, a matrix of correlation coefficients was calculated (Table 2).

Table 2

Matrix of correlation coefficients of the analysed factors

	CF	***ASH***	***SIL***	***TS***	***TOS***	**pH**
CF	1					
ASH	-0.41306	1				
SIL	0.54656	-0.38499	1			
TS	0.19373	-0.42162	0.01205	1		
TOS	0.23220	-0.51745	0.05740	0.99410	1	
pH	-0.03143	0.23781	-0.19331	-0.21054	-0.22712	1

As it can be seen from the correlation coefficient matrix, *TOS* and *TS* have a strong autocorrelation with each other, while *TOS* and *TS* have a moderate autocorrelation with *ASH*, but the pH value has a very weak effect on *CF*, so these three parameters (*TS*, *TOC*, pH) are excluded from further analysis. The correlation matrix also shows that *ASH* and *SIL* have stronger correlations with the resulting factor (*CF*), also, coefficients of these factors have opposite signs, thus potentially may have a significant summary effect on *CF*.

Summary of multivariate regression analysis of influence of *ASH* and *SIL* on *CF*) in biogas plants is shown below (Table 3).

Table 3

Summary of multivariate regression analysis

Multiple R	0.58901
R Square	**0.34694**
Adjusted R Square	0.23809
Standard Error	0.13892
Observations	15

Note: Multiple R – multiple correlation coefficient; R Square – coefficient of determination; Adjusted R Square – coefficient of determination adjusted according to number of independent variables in a model; Standard Error – standard error of the mean.

The coefficient of determination is 0.347, which indicates that 34.7% of the variation in the biogas plant power factor (*CF*) can be explained by the regression model that includes ash and silage content in input biomass as factors. The results of the analysis of variance are shown in Table 4.

Table 4

Results of analysis of variance (ANOVA)

	Df	***SS***	***MS***	***F***	***p***
Regression	2	0.12304	0.06152	3.18755	0.07757
Residual	12	0.23160	0.01930	–	–
Total	14	0.35465	–	–	–

Note: *Df* – number of degrees of freedom; *SS* – sum of squared deviations; *MS* – dispersion; *F* – actual value of the *F*-test; *p* – *p*-value of *F*-test.

The maximum probability P of assuming that the capacity factor of the biogas plant can be explained by the given linear regression model is calculated as follows:

$$P = (1 - p) * 100 \tag{2}$$

where P – maximum probability, %.

The maximum probability that a given multivariate linear regression model is statistically reliable is 92.2%. Further improvement in statistical significance can be achieved by increasing the number of observations or by using other types of equations for the model, such as non-linear equations.

Coefficients and their statistical characteristics for given multivariate linear regression model are shown in Table 5.

Table 5

Coefficients for multivariate linear regression equation

Parameter	**Coefficients**	**Standard Error**	***t*-stat**	***p*-value**	**Lower 95%**	**Upper 95%**
Intercept	0.72096	0.15218	4.73734	0.00048	0.38937	1.05255
ASH	-0.06812	0.07238	-0.94116	0.36518	-0.22585	0.08959
SIL	0.26328	0.14626	1.79999	0.09703	-0.05541	0.58196

As it can be seen from Table 5, the coefficients are statistically reliable with maximal probability of 99.95, 90.23 and 63.48% for intercept, silage proportion and ash percentage in silage respectively. Using the coefficients in Table 5, multivariate linear regression equation is as follows:

$$CF = 0.72096 - 0.06812 * ASH + 0.26328 * SIL \tag{3}$$

Where, *CF* – capacity factor of biogas plant; A*SH* – percentage of ashes in silage biomass;
SIL – proportion of silage in input feedstock.

The purpose of this analysis is also to clarify the threshold value of the percentage of total dry matter of silage between the 2 subgroups of biogas plants, one of which includes plants using silage with a relatively high total solids content, which allows silage to be stored without leakage, and the other subgroup includes biogas plants using silage with a relatively low dry matter content, which may result in leakage from the silage piles during storage. In order to find the optimum threshold value, all 15 biogas plants were divided into 2 subgroups, where the first subgroup included biogas plants with silage dry matter content equal to or higher than the threshold and the second subgroup included plants with silage dry matter content lower than the threshold. Statistical analysis was performed assessing the probability of rejecting the null hypothesis of equality of *CF*, *TS*, *TOC*, *ASH* and pH between the two subgroups at a given *TS* threshold using the MS Excel t-test function (Table 6).

Table 6

T-test p-values **for pairs of subgroups with different TS thresholds**

TS threshold, %	***n*1**	***n*2**	***CF***	***ASH***	***TS***	***TOS***	**pH**
31.9	6	9	0.1052	0.1595	0.0001	0.0001	0.3946
30.5	7	8	0.0489	0.0993	0.0002	0.0002	0.3058
29.9	**8**	**7**	**0.0181**	**0.0115**	**0.0004**	**0.0002**	**0.0438**
29.6	9	6	0.1095	0.0093	0.0008	0.0004	0.0336
28.8	10	5	0.2317	0.0016	0.0015	0.0006	0.0347

As it can be seen from Table 6, each pair of subgroups had same number (15) of biogas plants within all pairs of subgroups. Minimum *t-test p-values* for all parameters was obtained for a pair of subgroups having total solid (*TS*) percentage in silage equal or above 29.9% (Table 6, Fig 1).

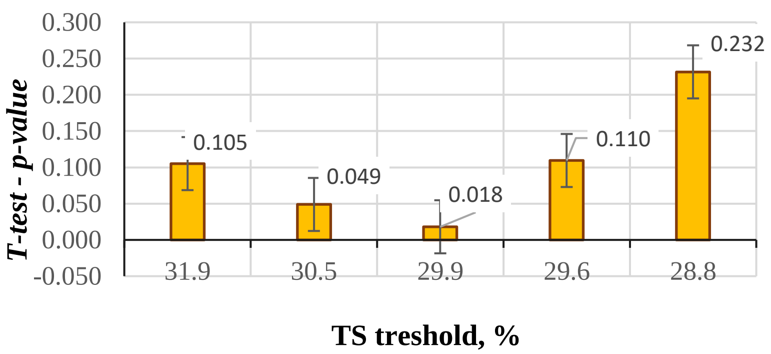

Fig. 1. ***P*-values for the null hypothesis of equality of CF means depending on the total solid (*TS*) threshold separating a subgroup with a low *TS* value from another subgroup with a high *TS* value within a pair of subgroups**

As shown in Fig. 1, the minimum p-values of the t-test between the two subgroups paired with the TS content in silage thresholds of 29.9% and 30.5% are less than 0.05, which means that the null hypothesis of equality of means of the parameters can be rejected with a probability above 95%.

As a result, opposite hypothesis can be accepted confirming that mean CR value for first subgroup including biogas plants with TS content in silage equal or above 29.9 % have higher mean CF value (0.812) compared to biogas plants with TS content in silage below 29.9 % which have lower mean CF value (0.645). For TS threshold 29.9 %, statistical analyses showed significant differences in mean CF values 0.812 or 0.645 in first or second subgroups, respectively, or showed that mean CF value for subgroup with higher TS content in input silage is by 20.6 % higher compared to subgroup with lower TS content.

The found TS threshold value range 29.9 – 30.5 % also conforms with recommended TS content 30 % in silage for silage producers, specified in the regulations [15] as the threshold above which no leakage of nutrient leakage from silage during storage is unlikely [15]. This is a very important outcome for biogas plant managers drawing attention that total solid (dry matter) content in silage should be above at least 30% during its preparation. the biodegradation of silage, that can be indicated by the increased percentage of ASH in silage, should be prevented by minimising oxygen ingress into the silage stacks during storage and removal. Also, other different factors should be taken in account while harvesting, storage, and feed-out silage biomass [16-17]. Further investigations are needed to investigate other major factors, e.g. organic load, biogas plant management practices, capable to significantly influence the energy effectiveness of biogas plants.

Conclusions

1. The statistical analysis showed that 34.7 % of the variation in the electric capacity factor of the biogas plant can be explained by a regression model including ash content in silage and silage content in feedstock as factors. The maximum probability that multivariate linear regression model is statistically reliable is 92.2 %. Given that the efficiency of biogas plants is influenced by many factors, the resulting two-factor combination model can be regarded as useful as it explains more than one third of all variations in biogas plant efficiency with statistically acceptable confidence.
2. Statistical analysis shows that the null hypothesis of equality of parameter means between two subgroups, where the first subgroup has relatively high and second relatively low TS content in input silage, can be rejected with a probability greater than 95 % for all investigated parameters, including the capacity factor. Investigated mean CF value in the subgroup with TS content in silage equal to or above 29.9 % is 20.6 % higher compared to the mean CF value in subgroup with lower TS content. It is recommended for all silage producers to maintain the total solids content of the silage above 29.9 % to prevent a decrease in the energy efficiency of the biogas plant, as well as to reduce nutrient losses through runoff from the silage storage
3. Biogas plant electric capacity factor can be used to evaluate energy-efficiency of biogas cogeneration plants and effectiveness of use of biomass resources, e.g., silage, for biogas production.
4. In future studies, other important factors such as organic load, substrate mixing in digesters, biogas plant management, and others should be included to develop a more sophisticated statistical model, which will give more detailed insight into the factors affecting the energy efficiency of biogas plants.

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Author contributions

Indicate the contribution of each author. Example: Conceptualization, I.P. and LP.; methodology, I.P; software, LP; validation, L.P. and I.P.; formal analysis, L.P.; investigation, L.P. and I.P.; data curation, LP; writing – original draft preparation, LP.; writing – review and editing, I.P.; visualization, L.P.; project administration, I.P.; funding acquisition, L.P. All authors have read and agreed to the published version of the manuscript.

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