ANALYSIS OF FACTORS INFLUENCING ENERGY EFFICIENCY OF BIOGAS PLANTS

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Abstract. The number of biogas plants in Latvia has decreased by 9 plants, from 56 in 2017 to 47 in 2022. One of the reasons for this decrease in the number of biogas plants is low energy efficiency. The energy efficiency factor is influenced by different factors. Factors influencing the operation of the 49 biogas plants in 2020 were assessed, including the factor Installed electric power that is not changeable by the plant operator. Other factors constitute a group of factors that can be compensated in daily operation like a proportion of input biomass. The parameters of all factors were analyzed using statistical methods. Results of analyses show that there is no single factor having the effect on the capacity factor with statistically acceptable reliability. However, correlation analyses and the obtained linear regression revealed two most significant factors, i.e. the proportion of manure (MA) and proportion of silage (SIL) in feedstock whose combination gives statistically significant linear equation for assessment of changes in the capacity factor (CF) MAof biogas plant. This two-factor model can be used to evaluate the capacity factor of a biogas plant with a combined input of manure and silage in Latvia.

Keywords: anaerobic biogas digestate efficiency energy fermentation.

Introduction

Biogas production in plants through anaerobic fermentation (AF) is considered as an environmentally friendly method for producing of energy and organic fertiliser. Number of biogas plants decreased from 56 in 2017 to 47 in 2022 in Latvia, mostly due to low energy and economic efficiency of biogas plants operation. To assess the energy efficiency factors, data on 49 biogas plants in 2020 were collected and analysed.

Many studies examine the problems of biogas plants and propose various solutions for improvement of the energy and economic efficiency of biogas plants worldwide.

Significant factors affecting biogas plants operating are downtime periods for technical maintenance and repair services. Long term experiments provided at biogas plants show that optimisation of the frequency of maintenance and repair measures can improve both technical and economical performance of biogas plants [1].

Significant impact on performance of biogas plants may have composition of substrate in feeding of anaerobic fermenter. Samples of 858 measurements, which were collected in a selected biogas station for a period of 2.5 years, were used to analyse differences in production of CH4, O2, and H2S outputs depending on the composition of inputs. From 17 inputs, 125 substrates were formed and significance of the influence of individual substrates was assessed by means of ANOVA analysis resulting in identification of 20 suitable and 11 unsuitable substrates for qualitive biogas production [2].

Variety of factors affecting the AF process itself are temperature, C/N ratio, ph., organic loading rate, additive use, volatile fatty acids, and different operational parameters, e.g. hydraulic retention time, particle size, agitating, toxicity, pressure in the digester and different pre-treatment techniques [3].

The effect of the fermenter temperature on biogas and methane production efficiency was evaluated during AF of duckweed. Two litre batch fermenters were incubated at room temperature, specific mesophilic (35 °C) and thermophilic (50 °C) conditions for 45 days period. The total biogas yield was achieved 7863.7 $ml \cdot L^{-1}$ in room temperature, 10376.6 $ml \cdot L^{-1}$ in mesophilic temperature and 9981.1 $ml \cdot L^{-1}$ in thermophilic temperature [4].

High effect on methane production can be achieved by co-digestion of different biomasses. Co-digestion of dairy manure (DM) and chicken manure (MA), and wheat straw (WS) performed better than individual digestion due to balanced C/N ratios. Mixtures of DM, MA and WS in co-digestion have higher synergetic effect compared to mixtures of single manure with wheat straw. C/N ratios in the range of 25:1 and 30:1 were found as optimal for digestion performances because of stable pH and low concentrations of TAN and free NH3 [5].

Biogas production effectivity can be largely increased by addition in substrate micronutrients. The effect of addition of typical feed supplement (used for dairy cattle usually) on methane production from dairy manure and silage was investigated. The nutrient source contained in typical feed supplement was the following: crude fibber 5.6%, crude oils and fats 3.7%, organic phosphorus 0.67%, magnesium 0.5%, crude protein 17.9%, crude ash 7.1%, calcium 0.7%, sodium 0.35%, zinc oxide 76 $mg \cdot kg^{-1}$, vitamin E 30 $mg \cdot kg^{-1}$, sodium selenate 0.6 $mg \cdot kg^{-1}$, calcium iodate 2 $mg \cdot kg^{-1}$, magnesium oxide 61 $mg \cdot kg^{-1}$, copper sulphate 30 $mg \cdot kg^{-1}$, and ferrous sulphate monohydrate 25 $mg \cdot kg^{-1}$. The specific biogas yield increased with the increasing the dose of typical cattle feed supplement from 543 $L \cdot kg^{-1}$ VS in the control to the maximum value of 894 $L \cdot kg^{-1}$ VS. Nutrient supplementation did not enhance the methane content in biogas, however, an optimal dose of supplement is crucial in order to have a successful anaerobic digestion (AD) and low costs of the process. In this study, nutrient supplementation of 0.5% of the fresh mass considerably increased biogas production [6].

Inoculums used in the biogas fermenter may affect methane production in the AF reactor. The effect of inoculum type and organic loading (OL) on the biogas yield of sunflower meal and wheat straw was evaluated. For this purpose, lab scale batch experiments were conducted at OL of 2 g VS L-1 in 225 mL glass bottle using digested manure, acclimatized sludge, and septic tank sludge as inoculum. The highest biogas yield and volatile solids (VS) reduction of 768 $NmL \cdot g^{-1}$ VS and 78%, respectively, were observed from sunflower meal with digested manure. The reactor inoculated with digested manure also showed better buffering capacity in terms of the pH value [7].

Sometimes substrates for biogas have components, e.g. heavy metals, inhibiting biogas production. Anaerobic baffled reactor (ABR) filled with compost leachate was used for investigating the impact of organic load rate (OLR) on biogas production and changes of alkalinity and pH in substrate. In order to decline the inhibitor concentration on anaerobic microorganisms, zeolite was considered as a media and changes of biogas production were investigated in different filling ratios. The highest produced biogas at the filling ratios of 10 %, 20% and 30% were 0.6, 0.63 and 0.9 $L \cdot day^{-1}$, respectively. In all three filling ratios, concentration of ammonia increased following to increasing ORL, but it has no adverse effect on biogas production. Results showed that although compost leachate is a toxic substrate with high concentration of heavy metals, zeolite was able to reduce toxicity and a higher amount of gas was produced at higher zeolite content. In this research work, although the produced biogas was low, it was shown that gas production from toxic wastewaters like leachate from compost is possible [8].

Significant savings of energy needed for running of biogas plants can be optimisation of substrate mixing during the AF process. The process without batch agitation (stirring) was carried out in a barrel bioreactor located in the incubator, whereas the process with batch agitation was carried out in a rotating drum bioreactor (rotation speed: 0.1 min^{-1}). In both cases, total solids were 18.8 wt%. The processes were conducted discontinuously without any addition during 21-day period. The experiment confirmed the possibility of increasing the anaerobic biogas and methane production by very slow continuous rotation (0.1 min^{-1}) of the reactor during discontinuous start-up of the process. With the experimental batch, 32.5% more biogas and 28.3% more CH4 were produced as a result of this method of agitation [9].

The purpose of the current investigation is to find the factors having significant influence on the agricultural biogas plant capacity factor and to find out whether there is a statistically significant difference between the average power factor mean values of a group of biogas plants with different installed electrical capacities.

Materials and methods

Data for investigation were obtained from official state organization homepage [10], from permits on polluting activities issued for biogas plant operation [11], and from the previous research [12]. Data on 49 biogas plants operating in Latvia in 2020 were included in this research. For simplifying of estimation, it was assumed that recipe of biomasses in feedstock of the biogas plant was not changed during 2020.

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

$$CF = \frac{E_r * 100}{E_t} = \frac{E_r * 100}{P * h}, \tag{1}$$

where E_r – electric energy supplied from the biogas plant to the network by the cogeneration plant during the period, kWh;

E_t – theoretical maximal energy to be produced in the period, kWh;
P – rated (installed) electric power of the cogeneration station, kW;
h – number of hours in the period.

Data on the installed electric power and electricity supplied from the biogas plant to the network was obtained from the state agency [10].

Statistical parameters, including correlation coefficients, coefficients for multiple linear regression equation were calculated to evaluate the effect of individual parameters on the capacity factor (CF) of the biogas plant using standard methods with use of MS Excel in statistical calculations [13].

Results and discussion

The statistical indicators obtained for different parameters that can influence the capacity factor (CF) of the biogas plant, Table 1.

Table 1

Statistical indicators of the studied factors

No.	Factor*	N**	Mean	Standard dev.	Minimum	Maximum
1	CF	49	0.63	0.23	0.17	0.90
2	P	49	1.16	0.96	0.16	6.50
3	SIL	39	0.59	1.22	0.04	7.90
4	MA	40	0.48	0.28	0.00	1.00
5	SEW	12	0.09	0.07	0.00	0.23

*factors: CF – capacity factor; P; installed electric power of biogas plant; SIL – share of silage in digestate; MA – share of manure in digestate; WS – share of wastewater sludge in digestate.
**number of biogas plants having specific factor.

The results of statistical analysis of the differences in the mean value of the capacity factor (CF) between 3 subgroups of biogas plants with different installed electric power (P) assuming equal differences between subgroups are provided in Table 2.

Table 2

Results of evaluation of mean values of the capacity factor (CF) for 3 pairs of subgroups with different installed electric power

Pair of variables	Variable 1*	Variable 2	Mean 1**	Mean 2	*t* Stat	*t* Critical two-tail	*P*(*T* < = *t*) two-tail
1	0-0.499	0.500-0.999	0.402	0.717	-3.649	2.074	0.001
2	0-0.499	> = 1.0	0.402	0.618	-2.171	2.045	0.038
3	0.5-0.499	> = 1.0	0.717	0.618	1.448	2.020	0.155

*Range of installed electric power in a group of biogas plants;
** Mean value of installed electric power within a group of biogas plants.

Statistically significant differences (probability > 99.9% and > 96.2%) were obtained for two pairs of subgroups: first pair including biogas plants subgroups with installed electric power 0-0.499 MW and 0.5-0.999 MW, and the second pair including subgroups with 0-0.499 MW and more than 1.0 MW installed electric power.

No statistically significant difference in mean values of power factors (CF) was obtained for the third pair of subgroups, i.e. between the subgroup with installed electric power (P) 0.5-0.499 and subgroup of biogas plants with installed electric power above 1.0 MW.

The results of correlational analyses between all factors are shown in Table 3. As it can be seen from Table 3, correlation analysis revealed weak colleration between the factors SEW, P MAand the resulting factor CF , therefore, the factors SEW and P are skipped from further analyses.

To assess the influence of the two independent factors MA and SIL on the dependent factor CF multiple correlation analyses were provided, Table 4 and Table 5.

Table 3

Correlation analysis

	CF	P	MA	SIL	SEW
CF	1				
P	-0.11985	1			
MA	0.39842	-0.51244	1		
SIL	-0.29898	0.09651	-0.38762	1	
SEW	0.20696	0.1167	-0.30052	-0.12006	1

Table 4

Results according to statistical analyses ANOVA

Result	***df***	***SS***	***MS***	***F***	***Significance F***
Regression	2	0.299	0.150	3.704	0.035
Residual	33	1.334	0.040	-	-
Total	35	1.633	-	-	-

*Statistical parameters: *Df* – number of degrees of freedom; *SS* – sum of squares of deviations; *MS* - variance (sum of squares of deviations per degree of freedom); *F* – empirical value of the Fisher criterion; *Significance F* –probability that the null hypothesis is correct.

In this case *F* > *Fcrit*, so the null hypothesis is rejected and accepted the alternative hypothesis, which means that the share of manure (MA) and share of silage (SIL) have a significant effect on the biogas plant capacity factor (CF).

Table 5

Statistical parameters of multiple linear regression

Factor	**Coefficients**	**Standard Error**	***t* Stat**	***P*-value**	**Lower 95%**	**Upper 95%**
Intercept	0.599	0.113	5.300	0.000	0.369	0.830
MA	0.287	0.147	1.948	0.060	-0.013	0.586
SIL	-0.177	0.178	-0.997	0.326	-0.539	0.185

*Statistical parameters: ***Coefficients*** – the coefficients of this multivariate linear regression model equation; ***Intercept*** – the free term of the regression equation describing the mutual interaction between the factors MA and SIL.

As it can be seen in Table 5, the *P*-value of the coefficients of the variables MA and SIL are > 0.05, which means that the significance level of the coefficients MA and SIL is below 95%. But the P value of the coefficients is < 0.05 for the interaction of the factors MA and SIL, so the significance level of the interaction effect of MA and SIL on the capacity factor of the biogas plant is above 95%.

Two charts with the trend of CF in dependence on the changes of the share of manure (MA) and share of silage (SIL) in feedstock in biogas plants are shown in Fig. 1 and Fig. 2.

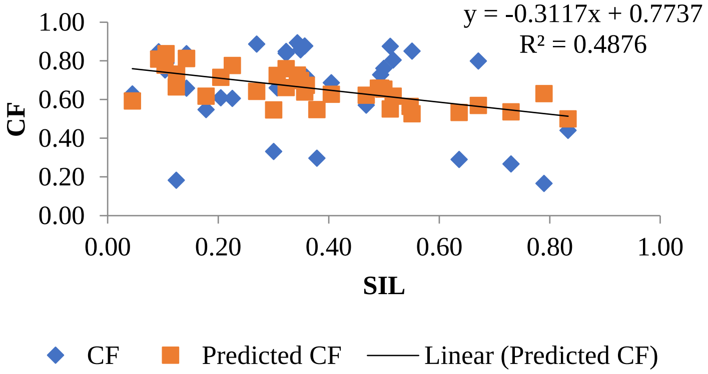

Fig. 1. **Capacity factor (CF) in dependence on share of silage (SIL) in feedstock**

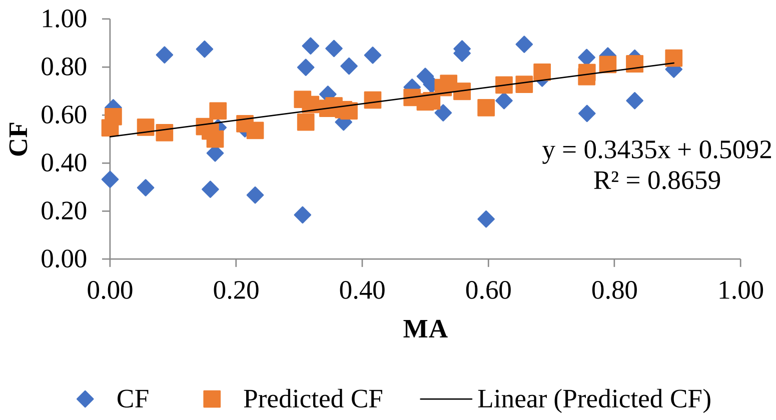

Fig. 2. **Capacity factor (CF) in dependence on share of manure (MA) in feedstock**

As it can be seen in Tables 4, 5 and Figures 1, 2, the proportion of silage explains 48.8% and the proportion of manure 86.6% of the change in the capacity factor of biogas plants. The two-factor model based on multiple correlation analysis is statistically significant with a probability value above 96.5%. The equation for the combined effect model is as follows (based on the equation coefficients in Table 5):

,

$$CF = 5.599 + 0.287MA - 0.177SIL \quad (2)$$

where CF – biogas plant capacity factor;
MA – share of manure in feedstock for biogas plant;
SIL – share of silage in feedstock for biogas plant.

The coefficients themselves in this equation are not statistically significant (see Table 5), however, the combined effect of silage and manure share in this two-factor model is statistically significant and can be used to evaluate the operation of biogas stations with the combined use of manure and silage as raw materials in Latvia.

Conclusions

1. Statistically significant differences (probability > 95%) were determined between the subgroup of biogas plants with an installed electric power of 0.000-0.499 MW compared to the subgroup of 0.500-0.999 MW or compared to the subgroup with an installed capacity above 1.0 MW.
2. Statistically insignificant difference (probability < 84%) was obtained between the subgroup of biogas plants with an installed electric power of 0.500-0.999 compared to the subgroup with an installed electric power above 1.0 MW.
3. Results of correlational analyses show that most significant factors influencing the biogas plant capacity factor (CF) are the share of manure (MA) and share of silage (SIL) in input of biogas plants. The two-factor model for assessment of the influence of silage and manure share on the capacity factor of biogas plants is statistically significant with a probability above 96.5% and can be used for evaluation of the performance of biogas plants with combined use of manure and silage in Latvia.
4. Further investigations should be provided for detailed assessment of significancy of other individual factors, e.g., technical maintenance/repair frequency, mixing process of substrate in fermenters, etc.

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Author contributions

Conceptualization, L.P. and I.P; methodology, L.P. and IP.; software, L.P.; validation, LP and I.P; formal analysis, I.P; investigation, L.P. and I.P.; data curation, L.P.; writing – original draft preparation, L.P.; writing – review and editing, I.P; visualization, L.P. Both authors have read and agreed to the published version of the manuscript.

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