Model of Electric and Heat Balance of Biogas Station

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Abstract. *This paper deals with the model of a biogas station. The introduction provides a description of principle employed in this model. The model works with data reflecting the quantity and type of the input biomass to determine the potential energy and offer a selection from various co-generation units. Other important input parameters comprise fermentors and mainly the material composition of their walls to help with determination of heat losses. The input parameters are accompanied by the energetic balance model for a Biogas Station (BPS) concerned. The next section of this paper provides verification of the model with respect to an actual BPS subject to a series of measurements. These measurements focus on electric and heat parameters. The outcome from these measurements was then used to obtain the energetic balance figure. The comparison of measurement results against the model produces slight deviations of the model from the real biogas station only. This paper has been processed pursuant to a long-term research on biogas stations. The biogas station model will be developed further to obtain a more detailed energetic balance for the biogas station.*

Keywords

Biogas station, energetic balance, heat losses, model, power losses.

1. Introduction

Each biogas station is a combined heat and power producing unit. Most of the current operators are focusing on the maximum utilisation of electric power. The heat producing remains mostly in the background with minor usage only. It would be mainly employed for the internal consumption within the BPS, that is warming up the fermentors and possibly even heating in the adjacent buildings. Biogas stations with contemporary design actually make use of some heat, since this parameter constituted one of the pre-conditions for award of subsidies. There are still options being explored to achieve a better efficiency. Using a greater amount of heat seems appropriate. To quantify the amount of heat available for further use, one needs to determine the internal consumption of heat within the BPS. That was the reason why we had opted to develop the model of BPS, which enables the operator to establish the overall energetic balance of the BPS.

2. Model Principle

The model processes the annual figures detailing individual input substrates to calculate the theoretical quantity of biogas produced. The total available power in the fuel is then calculated from this amount of biogas and biogas calorific value. The next step will be to select the type of one or more co-generation units by choosing from the drop-down menu with individual parameters. The model shows us whether the input power of Cogeneration Units (CGU) has exceeded the energy input from fuel. The next step requires entering of parameters for calculation of heat balance in the biogas station. That is the location of BPS – the options available show individual regions. Further details require to include parameters of fermentors, i.e. their height and radius. These values will be processed in the model to calculate the volume and individual areas for determination of heat losses. The list enables a selection of various materials that form the walls, floors and ceilings of fermentors respectively. The list is equipped with the database of most common materials with their heat transfer coefficients. The widths of individual layers are also required. The last important parameter is then represented by the length and char-

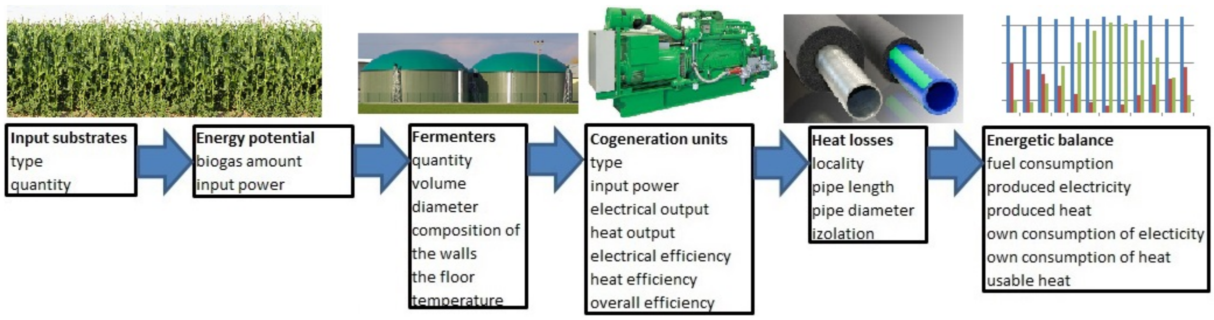

Fig. 1: Model block diagram.

acteristics of pipeline for transporting the heat from the CGU to fermentors. These parameters are used for calculation of heat losses and the internal consumption for warming the fermentors.

3. Operating the BPC Model

Using the values obtained from materials of biogas yield from various types of biomass, the amount of the biogas produced for the individual input substrates is calculated. It is merely a simple multiplication of the input amounts of biomass and the appropriate constant of biogas yield. Subsequently, the individual amounts of biogas produced from the individual ingredients are added up. The energy value of biogas from the biomass feedstocks is calculated from the amount of biogas produced per year as the product of this amount of biogas and the biogas calorific value. As the calorific value of biogas depends on the quantity of contained methane, it ranges from 18 to 25 MJ·m^3. This corresponds to the methane content of $48 - 68$ %. The biogas calorific value 18.61 MJ·m^{-3} was chosen, corresponding to the methane concentration of 50 %. This value was chosen deliberately for the lowest concentration which is normally present during the operation of biogas plants. The sum of all energy values of biogas produced from various types of biomass is the total energy value of biogas obtained from the biomass feedstocks. This value is used to calculate fuel input as a share of the total energy of biomass of the input biogas and the number of hours per year.

An important part of BPS are bioreactors. The basic parameters of the fermenter are calculated according to the desired height and radius of the base. According to the chosen composition of the walls of the bioreactor, the heat transfer coefficient is calculated in (W·m^{-2}·K^{-1}).

$$U = \frac{1}{\frac{l_1}{\lambda_1} + \frac{l_2}{\lambda_2} + \frac{l_3}{\lambda_3} + \frac{l_4}{\lambda_4} + \frac{l_5}{\lambda_5}}, \qquad (1)$$

where l_i is the thickness of each layer in meters (m), λ_i is the thermal conductivity coefficient (W·m^{-1}·K^{-1}) of the respective layer. During the next steps, the set temperature values will be stored in the bioreactor for the subsequent calculation of heat loss. The calculation will be terminated upon the completion of all the required parameters in other questionnaires.

The form is used to select types of cogeneration units. To facilitate their selection, the calculated value of the value of the total fuel input is already loaded. It was already calculated after entering the first form, i.e. the amount of the biomass feedstocks. After selecting cogeneration units from the list, the user can check the

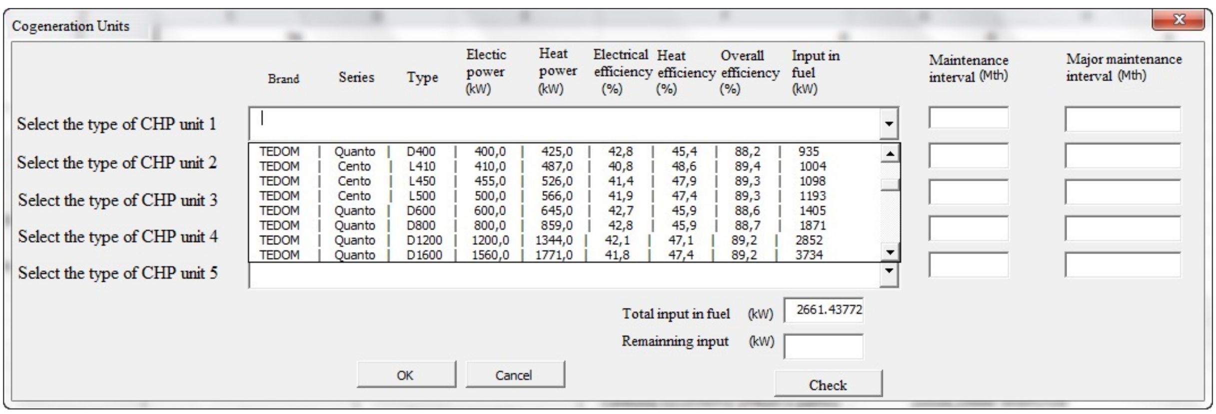

Fig. 2: Form cogeneration units.

input usage of the fuel. This button is called "Recalculation". After its activation, the value of the differential output will appear in the text field "Remaining output". This gives information on how much input power remains, or how much is missing for the operation of the selected cogeneration units. The remaining differential input is equal to the difference between the total input power of the biogas obtained from biomass, and the sum of the input power required for each of the selected cogeneration units:

$$P_{pz} = P_p - \sum_{i=1}^{5} P_p i, \tag{2}$$

where P_{pz} is the differential input (kW), P_p is the total input power in the fuel (kW) and P_{pi} is the input power of the relevant cogeneration unit.

The subsequent step after the optimization of the selected cogeneration units is the choice of the service interval of a regular service outage associated with the maintenance of cogeneration units. The length of the service interval is fixed for 3 hours. This period was determined based on the real biogas experience. This period gives the operator enough time for maintenance, which includes checking operational fillings, cleaning or the replacement of filters. In the case of the cogeneration unit, using a spark to ignite the mixture in the cylinder, also for cleaning or replacing the spark plugs. This value is used to calculate the number of monthly hours of the cogeneration unit operation.

The next step after selecting the cogeneration unit is the transition to calculate the heat loss. First, we calculate the heat loss from the pipe leading from the cogeneration unit to the bioreactors. After the selection of standard pipe diameters from the database, appropriate parameters are selected – outside diameter, inside diameter and wall thickness. Another important parameter is the thickness of the insulation, which is again selected from the used standard sizes. To calculate the heat loss in the pipe, it is necessary to enter the pipe length and the temperature of the medium in the output of the cogeneration unit. The last entry is the site selection, which assigns the corresponding average monthly outdoor temperature after the corresponding region is selected [1].

Consequently, the heat loss of the pipe Q_{ptr} (W) can be calculated:

$$Q_{ptr} = U_0 \cdot l \cdot (t_{in} - t_{out}), \tag{3}$$

where l is the length of the pipe (m), tin the medium temperature on the output of the cogeneration units (°C), t_{out} outdoor temperature (°C) – it corresponds to the selected location and the appropriate month.

After selecting the location, the heat loss of the bioreactors Q_f (W) can be calculated:

$$Q_f = Q_p + Q_s + Q_{st}, \tag{4}$$

where Q_p is the heat loss through the floor (W), Q_s the wall heat loss (W), Q_{st} the heat loss through the ceiling (W).

This is the total loss of the bioreactor, but the decomposition of biomass leads to the production of heat, this heat Q_b (W) is determined by the following formula:

$$Q_b = \beta \cdot V_f, \tag{5}$$

where β is the coefficient of heat production by the decomposition of biomass (W$\cdot$ m^{-3}), V_f is volume of fermenter (m^3). This coefficient was determined from practical measurement when the heat flowing for heating the bioreactor at known outdoor temperature was measured. The heat loss was calculated using the known structure composed of the bioreactor. The difference between the heat flowing to the bioreactor and

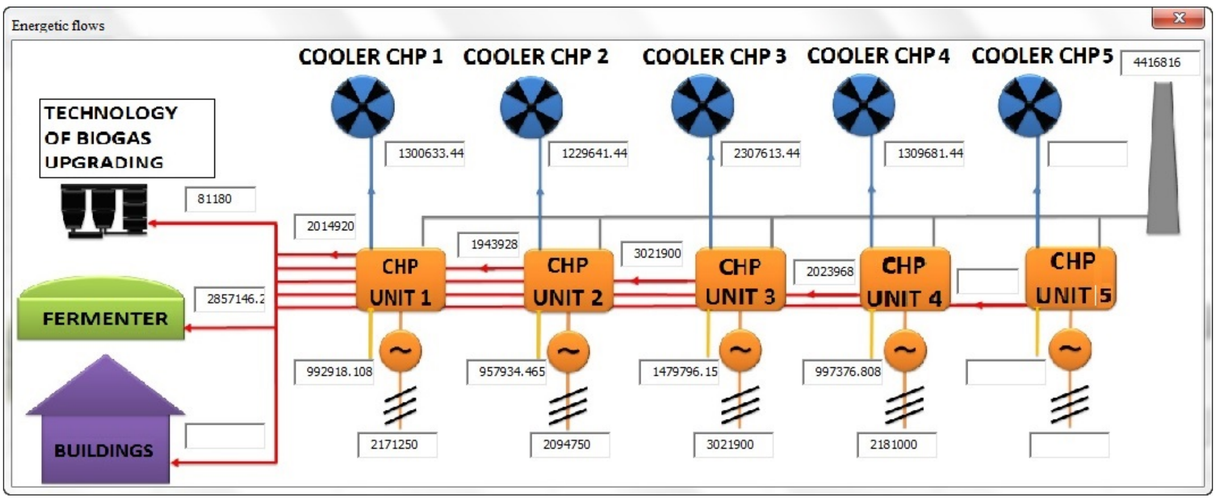

Fig. 3: Energetic flow scheme.

the heat loss of the fermenter, the value of the missing heat was obtained. The heat inside the bioreactor must be formed by decomposition of biomass, by dividing this value by the bioreactor volume, we obtain the value of the coefficient $\beta = 85$ W·m^{-3}.

The heat required for heating the bioreactor Q_v (W) is then given as the difference of the heat loss Q_f (W) and the heat resulting from biomass degradation Q_b (W):

$$Q_v = Q_f - Q_b. \tag{6}$$

For the total heat loss of the biogas plant Q_{bps} (W) the following formula then applies:

$$Q_{bps} = Q_{v1} + Q_{v2} + Q_{v3} + Q_{bp}, \tag{7}$$

where Q_{v1} (W) is the heat required for heating the first bioreactor, Q_{v2} is the heat required for heating the second bioreactor, Q_{v3} is the heat required for heating the after-bioreactor, Q_{bp} (W) the heat needed for the biogas treatment – to remove moisture (dehumidification):

$$Q_{bps} = V_{bp} \cdot \mu_{bp}, \tag{8}$$

where V_{bp} is the biogas consumption (m^3), μ_{bp} the coefficient of thermal energy consumption for dehumidification (W·m^{-3}), 1 (m^3) of raw biogas $\mu_{bp} = 18$ W·m^{-3}.

This value of the coefficient μ_{bp} was determined based on measurements carried out on real BPS, wherein the amount of heat flowing into the device for biogas treatment was measured while the value of biogas flowing into all the cogeneration units was read.

The result of all the specified parameters is the summarizing diagram of energy flows of the whole BPS per year.

- Energy required for biogas treatment – it is the energy that is needed to modify the biogas for the entire BPS according to the consumption of all cogeneration units.
- Energy for bioreactors – it is the energy that must be supplied for the bioreactors to cover the heat loss.
- Input energy to the cogeneration unit – it is the energy contained in the consumed biogas by the corresponding cogeneration unit according to the consumption H and operating hours per year.
- Electricity – it is the amount of electricity produced by the cogeneration unit according to the electrical output P_{el}, electrical efficiency η_{el} and operating hours.
- Thermal energy for own consumption – it is the energy supplied by the cogeneration unit for its own consumption BPS, it is calculated from its own heat consumption BPS divided by the proportional output of the relevant cogeneration unit.
- Cooling energy – it is the energy which must be diverted into the environment due to the cooling of the cogeneration unit – it is determined as the thermal energy produced by the cogeneration unit according to the heat output P_t, thermal efficiency η_t and operating hours, from which the heat, which the cogeneration unit supplies for its own consumption, is subtracted.
- Lost energy – it is the energy that is not utilized and its use is very problematic – it is the energy contained in flue gases – losses by incomplete combustion, heat losses of flue gas, because it cannot be cooled down to ambient temperature due to condensation in the exhaust system and insufficient thrust from the combustion chamber, the energy radiated by the surface of the cogeneration unit into the environment – every solid hotter than the environment radiates some heat. It is calculated as the difference of the input energy into the cogeneration unit and the output energy of the cogeneration unit, basically it is the remainder after deducting the electrical and thermal efficiency from 100 percent.

4. Model Verification

The model has been compared to the actual situation measured on the real biogas station. The Biogas Station (BGS) subject to measurement is located within the territory of Moravian-Silesian Region. This BPS is situated right in the premises of a pork farming enterprise processing mainly maize silage and pig's slurry. The main reason for this location is the source of pig's slurry for supply of fluid processed by the wet fermentation technology. Other reasons include the opportunity to use the waste heat in the heating system of the adjacent pigsty, the office building and the newly built harvest processing line in summer months. The biogas station comprises two fermentors, each offering the available volume of 1630 m^3 and the secondary fermentor with the capacity of 2090 m^3. The installed power capacity is equal to 1090 kW and the heat output is 1080 kW. Transformation of biogas into electric power is handled by four co-generation units. There are three identical compression ignition units delivering the output of 250 kWe and one spark ignition unit with the output of 340 kWe [2].

4.1. Measurement of Electric Parameters

The measurement was performed using an automatic digital measuring device Grid Analyser ENA 500 made by ELCOM, working in one-minute increments to measure and save effective values of phase voltages, currents per individual phase and power factors. The remaining values, i.e. effective, reactive, and apparent outputs were completed by calculation run in the device automatically.

Measurements of voltage were taken right at bus bars inside the distribution board RH1 and currents were measured with jaw currents converters MT-UNI using transformers 1500/5A already installed [2].

Fig. 4: Plant room and biogas processing unit.

4.2. Measurement of Heat and Internal Consumption of Heat Energy

The measurement taken by the contact flow meter produced mass flow rates of heat transfer fluids. Thermal element was used for measurement of temperature at the outlet and the return pipe, the specific heat capacities were determined and established per type of the flowing fluid and the temperature values obtained by measurement were processed using the Engineering Equation Solver software. This data served for calculation of heat output carried by individual pipelines [3].

Since the flow of biogas into CGUs was measured under conditions different to the particular standards, these values had to be converted with respect to the temperature and pressure of gas to establish the so called 'normal conditions, i.e. the temperature of 0 °C and the pressure of 101,325 Pa. Energy inputs from biogas to co-generation units were calculated using the converted biogas flow with respect to normal conditions and the calorific capacity of biogas determined by analysis of chemical composition of biogas. The chemical constitution of biogas was previously conducted per order from the biogas station operator [4].

The energy input from biogas entering the CGU and production of electric power on the generator in CGU were used to determine the electrical efficiency of CGU [4].

The BPS was run at almost the full nominal electric power, i.e. 1068 kW. The Zspark ignition unit was operated at the level of 340 kWe, which is the normal operating power. However, this is a unit with the nominal electric power equal to 350 kW. Yet this unit is operated at the output reduced by 10 kW here. That was because the contractor strove towards meeting the requirement for permitted installed capacity specified by the distribution grid operator. Two of the identical compression ignition units rated for 250 kW were operated at the output level of 249 kW, while the last CGU was operated at the level of 230 kW. The deviation of output from the nominal values ranges between 0 %, through 0.4 % up to the highest deviation of 4 %. The overall deviation from the nominal output from the entire BPS is then equal to 2 % [6].

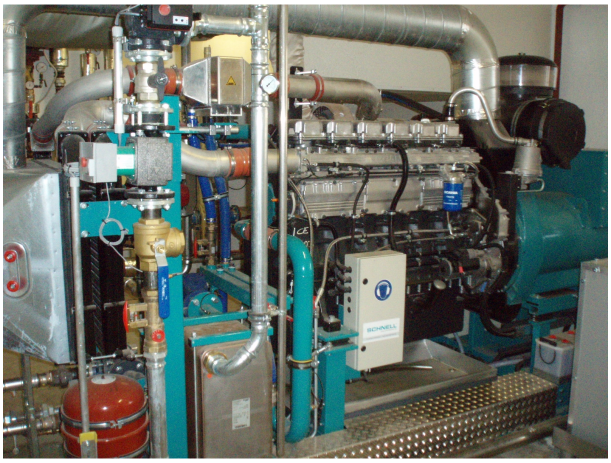

Fig. 5: Schnell ZV250-V5 co-generation unit.

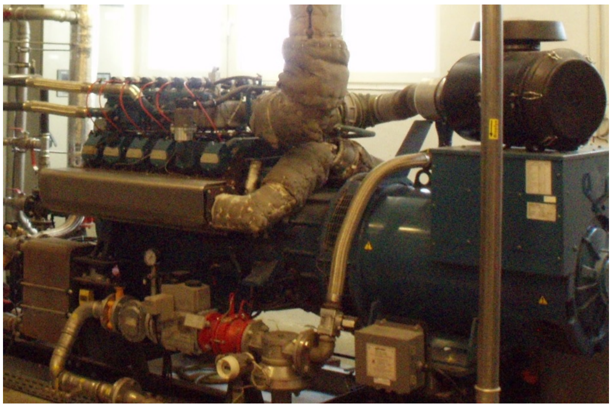

Fig. 6: Agrogen BGA222 co-generation unit.

The energy input from fuel has been obtained by conversion of the data reflecting the biogas flow into individual CGUs, its temperature and pressure. The electric input for the spark ignition unit was 864 kW, which is 22 kW below the level stated by its manufacturer. However, the value presented by the manufacture applies to CGUs operated at the full nominal output level. The energy input from fuel on two compression ignition units ranged around 565 kW, whereas the energy input for the last unit working at the lowest output level then approximated 545 kW. The deviation established in energy input from fuel then oscillated around 2.5 % in both the positive and negative terms. The manufacturer states the consumption may vary within 10 %. The heat output was measured using a flow meter and a thermal element at the outlets from individual CGUs; the values obtained were then converted. The output from compression ignition units ranged from 203 kW, through 219 kW, up to 220 kW, where the latter corresponds with the nominal output value. The compression ignition unit worked with the heat output of 359 kW that exceeds the value stated by the manufacturer. That was caused by operation of the CGU at a lower output level, since the machine is not working within the top efficiency region. The total heat output delivered by the BPS during the measurement period was equal to 1005 kW. These and further parameters can be found in the Tab. 1.

5. Energy Balance of BGS

The BPS model works with the values obtained from the manufacturer of individual co-generation units. As already mentioned in the introduction, the BPS model contains a database of biogas-fuelled CGUs from leading suppliers currently available on the market. To enable comparison of the values measured, the model had to be extended with older versions of co-generation units used within the specific BPS subject to measurement. These units have been undergoing continuous improvements untill now and the parameters of existing units would not match the actual units employed. This extension included specifically the parameters of units SCHNELL type ZV250-V5 [5] and AGROGEN type BGA 222 [6]. These parameters are also presented in the synoptic Tab. 2.

It shall be mentioned once again that the AGROGEN BGA 222 CGU is defined by these parameters for nominal electric power of 350 kW. The manufacturer states this unit may be operated at a reduced output rate, yet there are not detailed parameters supplied for it.

6. Comparison of Model with Measurement Results

The values produced by identical SCHNELL ZV250-V5 co-generation units were averaged for better comparison. The results of comparison can be viewed in the following synoptic tables for particular types of CGUs.

These tables show that the difference between this model and the actual measurement within the scope of several per cent only. The lowest deviation is 0.4 % and the highest one equals 5.2 %. This large deviation is caused by operation of the CGU at a level different from its nominal parameters. The average deviation is 2.4 % [7].

Tab. 1: CGU parameters measured.

	Schnell ZV250-V5	**Schnell ZV250-V5**	**Schnell ZV250-V5**	**Agrogen BGA222**
Energy input from fuel	566 kW	564 kW	545 kW	864 kW
Electric power	246 kW	249 kW	230 kW	340 kW
Electric efficiency	44.1 %	44.3 %	42.2 %	39.4 %
Heat output	220 kW	219 kW	203 kW	359 kW
Heat efficiency	38.9 %	38.9 %	37.3 %	41.5 %

Tab. 2: Theoretical parameters of CGUs.

	Schnell ZV250-V5	**Agrogen BGA222**
Energy input from fuel	549 kW	886 kW
Electric power	250 kW	350 kW
Electric efficiency	45.5 %	39.5 %
Heat output	220 kW	350 kW
Heat efficiency	40 %	39.5 %

Tab. 3: Comparison of parameters of Schnell ZV250-V5 CGU.

Schnell ZV250-V5	**Measurement**	**Model**	**Difference in values**	**Difference in percentage**
Energy input from fuel	560 kW	549 kW	11 kW	2.003643
Electric power	249 kW	250 kW	-1 kW	-0.4
Electric efficiency	44.5 %	45.5 %	-1 %	-2.35643
Heat output	217 kW	220 kW	-3 kW	-1.36364
Heat efficiency	38.75 %	40 %	-1.25 %	-3.30114

Tab. 4: Comparison of parameters of agrogen BGA222 CGU

Agrogen BGA222	**Measurement**	**Model**	**Difference in values**	**Difference in percentage**
Energy input from fuel	864 kW	886 kW	-22 kW	-2.48307
Electric power	340 kW	350 kW	-10 kW	-2.85714
Electric efficiency	39.4 %	39.5 %	-0.1 %	-0.3836
Heat output	359 kW	350 kW	-9 kW	2.571429
Heat efficiency	41.5 %	39.5 %	-2 %	5.183201

7. Conclusion

This paper deals with the BPS model and its verification against the actual parameters measured. The model has been operated with the CGUs selected to match the ones in the real BPS. Those are co-generation units Schnell ZV250-V5 and Agrogen BGA222. To enable comparison of the parameters measured with respect to the electric power, the heat output and the energy input from fuel against the data in the model, we have also compared the calculated parameters based on such values obtained by measurement; those are details of the electric power, the heat output and the overall efficiency. The values measured show a slight deviation from values of the model based on the nameplate parameters advised by the equipment manufacturer. This deviation progresses in both directions, i.e. towards the positive (the value measured gains higher levels exceeding the model parameters) as well as the negative values respectively. However, the deviation experienced in the best scenario is 0.4 %, while the worst one is then equal to 5.2 %. The average deviation is then approximately 2.4 %. We were dealing mainly with the verification of parameters inherent to the model and used as background data to establish the energy balance of biogas station. This model still is and will remain under development towards a more detailed energy balance of BPS, i.e. hours of operation, the amount of electric power produced, the amount of heat produced, the internal consumption of electric power, the internal heat consumption. The model should further assess the option to use any unused heat produced by co-generation units emitted to the surrounding environment, which is to improve the overall efficiency of the biogas station.

Acknowledgment

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