Synthesis of optimal biogas production system from multiple sources of wastewater and organic waste

M A Misrol, S R Wan Alwi*, J S Lim and Z A Manan

Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment (RISE), School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia.

*E-mail: syarifah@utm.my

Abstract. Biogas is one of the products that can be produced from wastewater or organic waste. Given the input streams for biogas digester can come from multiple sources rich in organic compound, optimization can be performed to maximise the production. In an industrial park with several types of industry, wastewaters and/or organic wastes from the industries or surrounding area can be used as feedstock for biogas production. Compared to conventional industrial park, Eco-Industrial Park (EIP) could be the appropriate platform for implementation as it advocates for industrial symbiosis through materials exchange and minimisation of waste, which are also in-line with the circular economy concept. In this study, a superstructure applicable for an EIP, which consists of multiple biogas sources, biogas digester, biogas upgrading, and biogas demands are developed. The model considers parameters which can affect biogas production quality and quantity such as Chemical Oxygen Demand (COD), Carbon/Nitrogen ratio (C/N ratio), and temperature. It also considers percentage of methane lost, removal efficiency of Carbon Dioxide (CO₂), electricity cost, capital cost of the selected biogas digesters as well as the cleaning and upgrading units. The main objective of the mathematical model is to maximise the profit generation from biogas generation for the EIP centralized biogas production plant. The model is solved by using General Algebraic Modelling System (GAMS) software. Case study conducted shows that anaerobic closed lagoon is selected as digester for the industrial wastewaters, while water scrubber is suggested as the biogas upgrading technology. A yearly profit is estimated at USD13,700,000, which is generated from selling of 279m³ of purified biogas. This may suggest that generating biogas from several sources of industrial wastewater and organic waste could be potentially feasible, thus reducing unnecessary pollutant while capturing the carbon source as an additional revenue stream.

1. Introduction

The circular economy concept promotes minimization of waste and fresh resources via the 3R (reduce, reuse, recycle) [1] or 6R (reuse, recycle, redesign, remanufacture, reduce, recover) [2] practice. These would not only improve the plant’s process, but also generates additional revenue stream through monetizing the potential carbon source available, which in this case, comes from the wastewater and organic waste.

Instead of being treated via processes that release the methane directly to the atmosphere, the biogas could be tapped as a source of renewable energy. In an industrial park context, a centralized wastewater treatment facility that could produce biogas from several wastewater streams that originated from
different industries is identified as one of the potential synergies [3]. Compared to conventional industrial park, the Eco-Industrial Park (EIP) could be the appropriate platform for implementation it advocates the dedicated philosophy i.e industrial symbiosis through materials exchange and minimisation of waste, which are also in-line with the circular economy concept.

However, the wastewater or organic wastes that are sent to the biogas digester may have different characteristics, which are not as homogeneous as they are sourced from an individual plant. This will open opportunity for optimization to be implemented in order to maximize the biogas production [4]. Drobez et al. [5] has conducted a study to optimize biogas production which was sourced from industrial wastewater and other several organic sources from poultry industry, combining heat integration via inclusion of heat exchanger. However, it does not consider COD content and C/N ratio to determine optimal biogas production.

Anokar et al. [6] has presented a predictive model for urban wastewater based on the Biological Oxygen Demand (BOD) as the most significant parameter. That said, the source for digestion is relatively homogenous. Thongnan et al. [7] has conducted a modeling study regarding co-digestion of farm waste and domestic organic waste, though it does not consider industrial wastewater as one of the feedstocks. Apart from wastewater, organic source from other sources e.g farm animal waste, kitchen waste and food, oil, and grease waste could also be useful as additional feedstock for the biogas production. A study done by Abdesahian et al. [8] indicates that 4589.49 million m$^3$ per year biogas can be produced from animal farm waste in Malaysia. Egieya et al. [9] has developed a multi-integer linear program (MILP) to optimize biogas supply from various types of biomass and manure as it also conducted economic and sensitivity analysis.

Study made by Mohtar et al. [10] analyses the economics of biogas plant for usage as bio compressed natural gas (bio-CNG). It considers selection of 6 biogas upgrading technologies in the model. However, specific parameters associated for each technology e.g methane loss and carbon dioxide (CO$_2$) removal efficiency were not accounted. Angelidaki et al. [11] and Sun et al. [12] have conducted review regarding the biogas upgrading technology as its (the biogas upgrading technology) efficiency in preventing methane loss, removing CO$_2$, and having lower electricity consumption are regarded as among of important items for attention, which will be considered in this study.

Overall, to the best knowledge of the authors, the study to optimize three important parameters at or prior to the biogas digester inlet, namely COD, C/N ratio, and temperature from different industrial wastewaters and organic waste is yet to be developed. Therefore, the motivation of this study is to develop mathematical model that could provide optimal biogas production from different sources of industrial wastewater and organic waste, at the same time considering selection of biogas upgrading technology, with the main objective is to maximize the profit generation. Considerations in selection of the biogas digester and the biogas cleaning as well as upgrading unit are also performed in the model. Section 2 will describe the superstructure and the mathematical equations used in the model. Information regarding the case study is provided in Section 3, while Section 4 provide the subsequent result and analysis. Section 5 will conclude main takeaway regarding the study conducted.

2. Superstructure and Model Development

2.1. Superstructure

Superstructure of the study is shown in figure 1 as follows:
An EIP ecosystem consists of multiple plants from different types of industry. It would have centralized facility to encourage materials exchange among the industries. Hence, in this context, it would have a centralized biogas facility that able to produce biogas from wastewaters, which are sourced from multiple industries. At the same time, it is also open to receive organic sources from surrounding domestic and agricultural activities, such as cow manure, kitchen waste, and food waste in order to maximize the carbon content conversion to biogas. The superstructure shown consists of multiple biogas sources, biogas digester, biogas upgrading, and biogas sets. The wastewater streams sourced each will have different wastewater strength with regards to the pollutant content. Given the adjustment of temperature, C/N and final average COD content are to be made in this study, it is assumed that the sources will not require pretreatment prior to the mixing.

The sources are grouped into two main streams i.e. the main sources and the additional sources. The former has different treatment objectives compared to the latter; it is intended to lower the COD as much as possible while tapping the biogas from the wastewater, whereas main objective for the organic sources is to harness the biogas production instead of leaving it ‘as-is’ i.e decompose naturally. Plus, COD removal of the additional sources in general is only 60% maximum, while COD removal of the main sources could be as high as 90%. Thus, it is proposed to have different digesters for both type of sources.

There will be two different technology configuration pertaining biogas digestion to be considered i.e continuous stirred-tank reactor (CSTR) and closed anaerobic pond. The selection of biogas purification consists of activated carbon and water scrubber for removal of Hydrogen Sulfide (H₂S), followed by technologies for removal of Carbon Dioxide (CO₂), namely pressure swing adsorption (PSA) and water scrubber. The model considers parameters which can affect biogas quality and quantity as mentioned earlier. The model is solved by using General Algebraic Modeling System (GAMS) software. Finally, it is applied to a case study to show its applicability.

Prior to be sent into the digesters, the sources streams will be mixed in order to ensure that the average COD content, C/N ratio content (specifically for organic sources only), and temperature are above or within or same the optimal condition for the biogas production. In this study, the optimal boundary of the parameters is shown in Table 1 as follows:
Table 1. Optimal boundary of the parameters in the mixers

| Parameter      | Optimal Value or Limits |
|----------------|-------------------------|
| COD content    | ≥ 10,000 mg/L           |
| C/N ratio      | ≥ 25 and ≤ 35           |
| Temperature    | 32°C                    |

There are two options regarding biogas digester technology specifically for the wastewater sources i.e CSTR and closed anaerobic pond, while all the organic sources will be digested in the separate CSTR. Biogas generated from both main streams will be sent to the biogas cleaning and upgrading unit as it will have two options of technology i.e. (1) activated carbon combined with PSA or (2) water scrubber. Details of both technologies are further described in Section 3. It is assumed that purified biogas from both options are able to produce methane up to 97% concentration. The demand point is assumed to be the natural gas pipeline with selling price of USD 6.5 per nm³.

2.2. Mathematical Formulation

Main objective of the model is to obtain maximum profit (Pr) from selling of the purified biogas. The list of equations for the model are listed as follows:

Objective function:
\[ Pr = Rv - C_{CostBg} - OMC_{ostBgCln} - OMC_{ostBgCl} - ECost_{BgCl} - MP \]  

\( Rv \) is revenue from selling of the purified biogas. \( C_{CostBg} \) stands for total annualized capital cost of the biogas digesters selected and \( OMC_{ostBg} \) is the associated total operation and maintenance cost. \( C_{CostBgCl} \) is total annualized capital cost of the biogas cleaning and upgrading technology selected, with associated operation and maintenance cost is termed as \( OMC_{ostBgCl} \). Electricity cost for the biogas digesters is assumed to be included in the \( OMC_{ostBg} \) while electricity cost for the biogas cleaning and upgrading technology is put as \( ECost_{BgCl} \). \( MP \) is the manpower cost.

Constraints:

Source-to-mixer flow rate constraint:
\[ F_{h}^{source} \] and \( F_{i}^{mix} \) are the flow rate of the sources and mixers respectively. \( B_{h,i} \) is a binary parameter to assign the sources h to the mixer i, where K is a large integer value to limit the flow rate from the sources of the intended mixer. COD content of each sources is \( C_{h}^{source} \) and the resulting average COD content at the mixer is \( C_{i}^{mix} \). Total COD content at set h and i are \( COD_{h}^{source} \) and \( COD_{i}^{mix} \) respectively. It is required for the average COD value in the mixer to be at more or equal to 10 kg per m³ in order to obtain higher yield of the biogas production. \( CN_{h}^{source} \) is the C/N ratio of the sources, thus \( CN_{i}^{mix} \) is the C/N ratio in the mixers. Only C/N ratio for organic sources is considered to require optimal C/N ratio as one of the condition to achieve optimal biogas production.

\[ K \times B_{h,i} = F_{h,i}^{source mix} \]  

\[ F_{h}^{source} = \sum_{i} F_{h,i}^{source mix} \quad \forall h \]  

\[ \sum_{h} F_{h,i}^{source mix} = F_{i}^{mix} \quad \forall i \]  

\[ COD_{h}^{source} = \sum_{i} F_{h,i}^{source mix} \times B_{h,i} \times C_{h}^{source} \quad \forall h \]  

\[ \sum_{h} F_{h,i}^{source mix} \times B_{h,i} \times C_{h}^{source} = COD_{i}^{mix} \quad \forall h, i \]
\[ C_{i_{mix}} = C_{i_{mix}} \times F_{i_{mix}} \quad \forall i \] (7)

\[ C_{i_{mix}} \geq 10 \quad \forall i \] (8)

\[ F_{i_{mix}} \times CN_{i_{mix}} = \sum_i F_{i_{source_{mix}}} \times CN_{i_{source}} \quad ; \ i = 2 \] (9)

\[ 25 \leq CN_{i_{mix}} \leq 35 \quad ; \ i = 2 \quad \forall i \] (10)

Temperature balance at the mixers:

\[ T_{h_{source}} \] is the temperature of sources and \( T_{i_{mix}} \) is temperature of the mixers. \( C_p \) is the specific heating value of water. Total energy that able to be withdrawn from the mixers is termed as \( Q_{total} \). Temperature of the organic sources are assumed to be at ambient temperature (32°C), thus only the 1st mixer is considered for potential energy withdrawal.

\[ F_{h_{source}} \times T_{h_{source}} \times C_p = \sum_i F_{i_{source_{mix}}} \times B_{i_{mix}} \times C_p \times T_{h_{source}} \quad \forall i \] (11)

\[ \sum_h F_{i_{source_{mix}}} \times B_{h,i} \times C_p \times T_{h_{source}} = F_{i_{mix}} \times T_{i_{mix}} \times C_p \quad \forall h,i \] (12)

\[ Q_{total} = F_{i_{mix}} \times \frac{C_p(T_{i_{mix}}-32)}{3600} \quad ; \ i = 1 \] (13)

Mixer-to-digester flow rate constraint:

Since \( F_{i_{mix}} \) has to be sent to digester(s), flow rate from the mixer is termed as \( F_{i_{mix}bg} \). \( F_{jbg} \) is the flow rate at inlet of the digester. \( B_{i,j} \) is a binary parameter to assign the streams from i to the digester j, where L is a large integer value to limit the flow rate from the mixers to the intended digester. \( C_{jbg} \) is the COD content in the digester which will be used to determine the amount of biogas produced.

\[ L \times B_{i,j} = F_{i_{mix}bg} \] (14)

\[ F_{i_{mix}} = \sum_j F_{i_{mix}bg} \quad \forall i \] (15)

\[ \sum_i F_{i_{mix}bg} = F_{jbg} \quad \forall j \] (16)

\[ C_{i_{mix}} = \sum_j C_{i_{mix}bg} \quad \forall i \] (17)

\[ \sum_j C_{i_{mix}bg} = C_{jbg} \quad \forall j \] (18)

Total production of biogas:

\( F_{jbg}^{bog} \) is the flow rate of biogas produced from the digesters. \( Eff \) is the production efficiency. \( Bgyield \) is the constant value of biogas produced per kg of COD removed, \( Bgdensity \) is the biogas density.

\[ F_{jbg} \times C_{jbg} \times Eff \times \frac{Bgyield}{Bgdensity} = F_{jbg}^{bog} \quad \forall j \] (19)

Digester-to-upgrading flow rate constraint:
\( F_{j,k}^{bg\text{cln}} \) is the flow rate from the digester to the biogas cleaning and upgrading unit. \( F_k^{cln} \) is the flow rate of the raw biogas received at the inlet of \( k \). \( X_k \) is the conversion yield of respective technology to produce purified biogas at amount of \( F_k^{cln\text{out}} \). Revenue from selling of the purified biogas is \( R_v \). \( R_k \) and \( A_k \) are the selling price in USD and the annual operating hour respectively.

\[
F_{j}^{bg\text{out}} = \sum_{k} F_{j,k}^{bg\text{out\text{cln}}} \quad \forall j \tag{20}
\]

\[
\sum_{j} F_{j,k}^{bg\text{out\text{cln}}} = F_k^{cln} \quad \forall k \tag{21}
\]

\[
F_k^{cln} \times X_k = F_k^{cln\text{out}} \quad \forall k \tag{22}
\]

\[
R_v = \sum_{k} F_k^{cln\text{out}} \times R_k \times A_k \tag{23}
\]

Capital, Operating and Maintenance Cost estimation:

\( CCostBg \) is the capital cost of the selected biogas digesters. \( CBg \) is the cost per m\(^3\) of the feed volume. \( \alpha \) is the power factor and \( Af \) is the annualized factor. Estimated cost for associated operating and maintenance cost for the selected biogas digesters, \( OMCostBg \) is multiplication of \( OMBg \) which is the percentage value of \( CCostBg \).

Both \( CBg \) and \( CBgCln \) are obtained via calculation based on the cost index formula:

\[
CBg \text{ or } CBgCln = BaseCost \left( \frac{l}{l_{base}} \right) \tag{24}
\]

Where \( BaseCost \) is cost of the system or unit based in certain years e.g 2007, while \( l \) and \( l_{base} \) are the current cost index (referred as 2018) and the cost index in year of the \( BaseCost \) is referred.

The same formula is principally applied for the biogas cleaning and upgrading. \( CCostBgCln \), \( CBgCln \), \( OMCostBgCln \), and \( OMBgCln \) are the capital cost of the selected cleaning and upgrading technology, cost per m\(^3\) of the feed raw biogas volume, associated operating and maintenance cost (excluding electricity cost), and the capital cost percentage value respectively.

\[
CCostBg = \sum_{j} ((CBg \times F_{j}^{bg})^\alpha)Af \tag{25}
\]

\[
OMCostBg = \sum_{j} OMBg \times CCostBg \tag{26}
\]

\[
CCostBgCln = \sum_{k} ((CBgCln \times F_k^{cln})^\alpha)Af \tag{27}
\]

\[
OMCostBgCln = \sum_{k} OMBgCln \times CCostBg Cln \tag{28}
\]

Electricity cost of the biogas cleaning and upgrading:

The electricity cost, \( ECostBgCln \), is given by multiplication of the electricity price (\( EP \)), cost per nm\(^3\) of raw biogas in USD (\( EC \)), annual operation hour (\( AOH_k \)) and \( F_k^{cln} \)

\[
ECostBgCln = \sum_{k} EP \times EC \times AOH_k \times F_k^{cln} \quad \forall k \tag{29}
\]

3. Case Study

The produced raw biogas from the digesters is assumed to possess 60% methane, 39.4% CO\(_2\), 0.2% nitrogen gas (N\(_2\)), and 0.4% H\(_2\)S. Properties of the sources are shown in table 2 follows:
Table 2. Properties of the sources

| Sources                          | Hourly Flow Rate (m³/h) | COD (mg/L)* | Temperature (°C) | C/N ratio (%) |
|---------------------------------|-------------------------|-------------|------------------|---------------|
| Wastewater from palm oil mill   | 20                      | 55,000      | 80               | N/A           |
| Wastewater from food industry   | 20                      | 1,120       | 32               | N/A           |
| Wastewater palm oil refinery    | 20                      | 10,000      | 60               | N/A           |
| Cow manure                      | 2                       | 17,400      | 32               | 23.6          |
| Food waste                      | 2                       | 682,600     | 32               | 28.0          |
| Fat, oil, and grease waste from | 2                       | 148,000     | 32               | 28.0          |
| kitchen waste                   |                         |             |                  |               |

*The value is same if the unit is converted to kg/m³ as per used in the model. Please refer the nomenclature list for details

In this study, density of the wastewater all are assumed at 1 metric ton/m³. Properties of the biogas digester options are given in table 3 as follows:

Table 3. Properties of the biogas digester technology options

| Sources                   | Base Cost (USD) | Operating and Maintenance Cost (USD) | References |
|---------------------------|-----------------|--------------------------------------|------------|
| CSTR                      | 1,395,000 (2007)* | 2% from capital cost                 | [13],[14]  |
| Closed anaerobic pond     | 168,000 (2007)*  | 15% from capital cost                | [13],[14]  |

*1USD = 3.26MYR in 2007

Properties of the biogas cleaning and upgrading technology are given in table 4 follows:

Table 4. Properties of the biogas cleaning and upgrading technology options

| Technology                | Methane losses (%) | CO₂ removal efficiency (%) | Base Cost (USD) | Maintenance Cost (USD) | Electricity Consumption (kWh per nm³ biogas) | References |
|---------------------------|--------------------|----------------------------|-----------------|-----------------------|---------------------------------------------|------------|
| AC + PSA                  | 2%                 | 98%                        | 1.39 million USD for 500nm³/h raw biogas input (2009)* | 2% from capital cost                          | 0.3                                      | [15],[16]  |
| Water scrubber            | 1%                 | 95%                        | 1.38 million USD for 500nm³/h raw biogas input (2009)* | 3% from capital cost                          | 0.275                                    | [15]       |

*1 Euro = 1.11 USD

Other parameters used for in model is shown via table 5 below:
### Table 5. Other parameters used in the mathematical model

| Parameters                              | Value                                      |
|-----------------------------------------|--------------------------------------------|
| Annual operating hours                  | 8000 hours                                 |
| Operating years of the system           | 20 years                                   |
| Electricity cost                        | MYR 0.355* per kWh                         |
| Selling price of the purified biogas    | USD 0.3 per nm³                            |
| Specific heating value of the stream    | 4.2 kJ per K kg                            |
| Biogas production yield                 | 75% for the wastewater streams             |
|                                        | 60% for the organic sources                |
| Biogas density                          | 1.12 kg/m³                                 |

*1 USD = 4 MYR as current exchange rate

### 4. Result and Discussion

The non-linear program (NLP) model is run via GAMS version 25.1.2 in a computer with processor capacity of IntelCore i3-8130U 2.2GHz. It was solved using CONOPT solver as the solver provides a locally optimal solution, suggesting that feasible solution is exist for the model. Execution time takes less than 1 second. The average COD content for the wastewater sources combined is 22,000 mg/L. Specific for the organic waste, the average COD content and C/N ratio are 282,000 mg/L and 26.5 respectively. An estimated 1.77MW of energy is able to be withdrawn from the mixer while the adjusting the temperature to the required operating condition. The optimal network selected is shown in figure 2 follows.

![Figure 2](image_url)

**Figure 2.** The optimized superstructure

The optimization result suggests closed anaerobic pond as the digester type for the wastewater streams and water scrubber is chosen for the biogas cleaning and upgrading technology. Total annualized capital cost for the biogas digesters and the water scrubber are calculated at USD 31,900 and USD 87,000 respectively. Combined operating cost of the selected biogas digesters and biogas cleaning and upgrading unit is USD 85,200. Electricity cost is USD 88,183. Revenue generated is calculated at USD 669,800 per year while profit obtained is USD 377,600. Translated into local currency, it is equal to MYR 1,510,400 of yearly profit.
An estimated amount of 452 nm$^3$ raw biogas will be produced from both digesters as it will be further sent to the water scrubber for cleaning and upgrading. Total annual revenue generated is based on selling of 279 nm$^3$ of purified biogas.

5. Conclusion
In this study, a mathematical model to provide optimal production of biogas from multiple sources of wastewater and organic waste in centralized EIP site level is proposed. Optimization of the input streams considering the COD, temperature, and C/N ratio has been performed together with selection of the digester and cleaning and upgrading technologies in order to provide optimal condition pertaining the biogas production. The case study conducted shows that the presented superstructure could be possibly developed in real industrial world. That said, the model, which is planned to be further expanded in the next study, will include consideration of pH, piping, compression, and associated logistics costs. It is also to consider opportunity to recycle or treat the effluent and to monetize the solid waste, thus the project feasibility could be comprehensively determined prior to any potential real engineering works.

Nomenclature

Sets
$h$ Source
$i$ Mixer
$j$ Biogas digester
$k$ Biogas upgrading

Parameters
$K$ Integer value to limit the flow rate from $h$ to $i$
$L$ Integer value to limit the flow rate from $i$ to $j$
$B_{h,i}$ Binary parameter to assign the sources $h$ to the mixer $i$
$F_{h,source}$ Flow rate of source $h$ (m$^3$/h)
$C_{h,source}$ COD content of source $h$ (mg/L)
$C_{h,N,source}$ C/N ratio of source $h$ ($\%$
$T_{h,source}$ Temperature of source $h$ ($^\circ$C)
$C_p$ Specific heat capacity of water (4200 kJ/m$^3$ K)
$Eff$ COD removal efficiency ($\%$
$Bgyield$ Biogas production yield ($\%$
$Bgdensity$ Biogas density (kg/m$^3$)
$X_k$ Conversion yield of respective technology to produce purified biogas ($\%$
$R_k$ Selling price of purified biogas (USD per nm$^3$)
$A_k$ Annual operating hours (hours)
$BaseCost$ Cost of the base equipment/system (USD)
$I_{base}$ Cost index of the base equipment/system
$I$ Cost index of the selected equipment/system
$\alpha$ Power factor
$Af$ Annualization factor
$OMBg$ Percentage of operating and maintenance cost of biogas digester from selected technology ($\%$
$EP$ Electricity price (USD)
$EC$ Electricity factor per capacity of biogas cleaning and upgrading system installed (kWh/nm$^3$)
$AOH_k$ Annual operating hours (hour)
Variables

\[ F_{\text{source mix}}^{h_i} \]
Flow rate from source h to mixer i (m³/hour)

\[ F_i^{\text{mix}} \]
Flow rate at mixer i (m³/hour)

\[ COD_{\text{source}}^h \]
Total COD of sources h (kg)

\[ COD_{\text{mix}}^i \]
Total COD at mixer i (kg)

\[ C_i^{\text{mix}} \]
COD content for each mixer stream i (kg/m³)

\[ CN_i^{\text{mix}} \]
Cumulative C/N ratio value at mixer i (kg)

\[ T_i^{\text{mix}} \]
Temperature for each mixer stream I (°C)

\[ Q_{\text{total}} \]
Total energy able to withdrawn from mixer I (MW)

\[ F_{i,j}^{\text{mix bg}} \]
Flow rate from mixer i to biogas digester j (m³/hour)

\[ F_j^{\text{bg}} \]
Flow rate at biogas digester j (m³/hour)

\[ C_j^{\text{mix bg}} \]
COD content from mixer i to biogas digester j (kg/m³)

\[ C_j^{\text{bg out}} \]
Amount of raw biogas generated at j (nm³)

\[ F_{j,k}^{\text{bg Clin}} \]
Flow rate from raw biogas generated at j to biogas cleaning and upgrading system k (nm³)

\[ F_{k}^{\text{Clin}} \]
Flow rate of raw biogas at biogas cleaning and upgrading system k (nm³)

\[ F_k^{\text{out}} \]
Amount of purified biogas produced from k (nm³)

\[ R_v \]
Revenue generated from selling of purified biogas (USD)

\[ CBg \]
Capital cost of biogas digester (USD)

\[ CBgClin \]
Capital cost of biogas cleaning and upgrading system (USD)

\[ CCostBg \]
Annualized capital cost of selected biogas digester (USD)

\[ CCostBgClin \]
Annualized capital cost of selected biogas cleaning and upgrading system (USD)

\[ OMCostBg \]
Operating and maintenance cost of biogas digester (USD)

\[ OMCostBgClin \]
Operating and maintenance cost of biogas cleaning and upgrading system (USD)

\[ ECostBgClin \]
Electricity cost of the biogas cleaning and upgrading system (USD)

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