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ORIGINAL PAPER

Biogas production from multiple feedstock at the district-level centralized facility for multiple end-use options: a case study in Johor Bahru, Malaysia

Mohd Arif Misrol[1] · **Sharifah Rafidah Wan Alwi**[1] · **Jeng Shiun Lim**[1] · **Zainuddin Abd Manan**[1]

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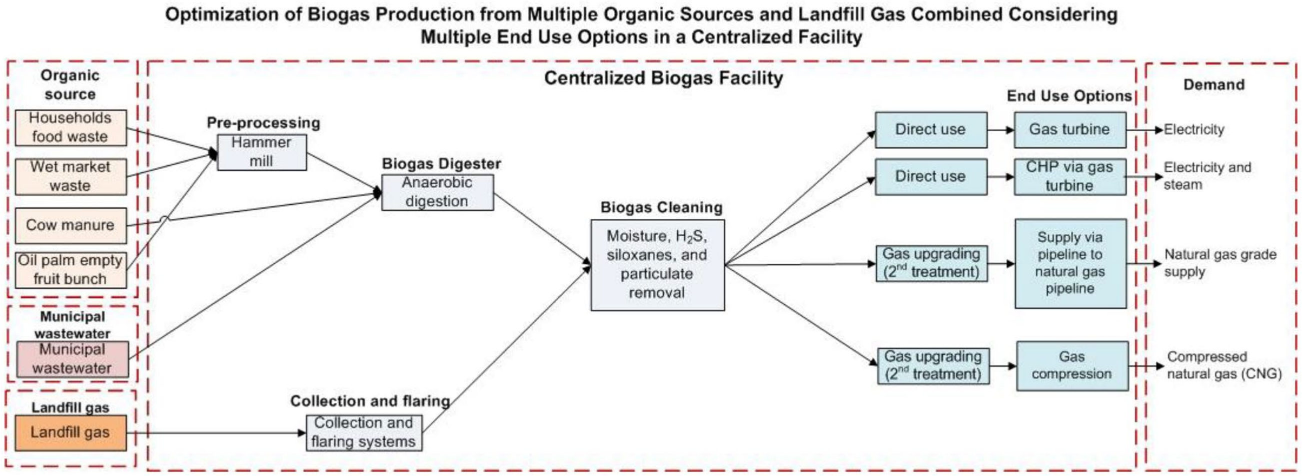
Abstract

In the 7th Agenda of the United Nations Sustainable Development Goals, sustainable energy is one of the main interests and it should be renewable. Biogas is considered as one of the renewable sources of energy. In maximizing biogas production, the challenge is to establish feasible processes considering multiple factors as it can be produced from more than one type of feedstock. In this study, the biogas production's potential is assessed at the district level of Johor Bahru, Malaysia, through mathematical modelling approach. The potential feedstocks include food waste, wet market waste, domestic wastewater, agricultural waste, and animal waste. Landfill gas collection is also considered as the gas will be mixed with the anaerobic digester biogas in a centralized facility mode. The availability of the sources is based on the literature and the associated government departments. Multiple options of end-use of the biogas are considered. Apart from the techno-economic parameters regarding the involved processes, the collection and pre-processing costs of the applicable feedstocks are also considered. 14.5 MW of renewable electricity and 25 t/h of steam can be generated through the processes indicated by the optimal solution of the mixed-integer nonlinear integer model. Collection, transportation, pre-processing costs of the applicable organic wastes, and the end-use technology costs are the critical items that contribute significantly pertaining the project's economics. The study's result provides practical insight into how the proposed idea can be implemented in the real world.

Graphic abstract



Keywords Biogas · Industrial symbiosis · Optimization · Mathematical modelling · Renewable energy · Anaerobic digestion

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Extended author information available on the last page of the article

List of symbols

Set(s)

h	Source(s)
i	Pre-processing
j	Biogas digester
k	Landfill gas
l	Biogas cleaning
m	End-use option(s)
w	Municipal wastewater
p	Properties of the source(s)
c	Methane content in the biogas

Parameters

F_h^s	Flow rate of source (t/h)
$C_{h,p}^s$	Properties of source (%)
$B_{h,i}^{\mathrm{spr}}$	Binary parameters to limit flow rate from source to pre-processing
$B_{h,j}^{\mathrm{sbd}}$	Binary parameters to limit flow rate from source to biogas digester
K	A relatively large value
A^{pr}	Pre-processing recovery constant
F_w^{mw}	Flow rate of municipal wastewater (t/h)
$\mathrm{Bg}^{\mathrm{yld}}$	Biogas yield (m^3/t of VS)
F_k^{lg}	Flow rate of landfill gas (m^3/h)
A^{bcl}	Biogas cleaning recovery constant
F_m^d	Flow rate of demand (m^3/h)
A_m^{gt}	Binary parameter to limit the associated calculations only to be applicable for electricity generation via gas turbine option
GCF	Gross capacity factor (%)
$\mathrm{CV}^{\mathrm{CH4}}$	Calorific value of methane (MJ/m^3)
$\mathrm{Eff}^{\mathrm{egte}}$	Electricity efficiency of gas turbine (%)
$\mathrm{Eff}^{\mathrm{pgte}}$	Electricity efficiency considering parasitic load of gas turbine (%)
$\mathrm{CF}^{\mathrm{MWkW}}$	Conversion factor from MW to kW (kW/MW)
CF^{hs}	Conversion factor from s to h (s/h)
A_m^{chp}	Binary parameter to limit the associated calculations only to be applicable for CHP via gas turbine option
$\mathrm{Eff}^{\mathrm{echp}}$	Electricity efficiency of CHP gas turbine (%)
$\mathrm{Eff}^{\mathrm{pchp}}$	Electricity efficiency considering parasitic load of gas turbine (%)
$\mathrm{Eff}^{\mathrm{hchp}}$	Heat recovery efficiency of CHP gas turbine (%)
$\mathrm{Stm}^{\mathrm{lh}}$	Latent heat of steam (MJ/t)
AWH	Annual working hour (h/y)
P^{ect}	Selling price of generated electricity (USD/kWh)
P^{stm}	Selling price of supplied steam (USD/t)
A_m^{ngp}	Binary parameter to limit the associated calculations only to be applicable for supplying natural gas via pipeline option
P^{ng}	Selling price of natural gas (USD/MMBtu)
$\mathrm{DF}^{\mathrm{ngp}}$	Discount factor of selling natural gas (%)
$\mathrm{CF}^{\mathrm{MJmbtu}}$	Conversion factor from MJ to MMBtu
A_m^{cng}	Binary parameter to limit the associated calculations only to be applicable for CNG option
$\mathrm{Eff}^{\mathrm{cng}}$	CNG process efficiency (%)
$\mathrm{CF}^{\mathrm{m3l}}$	Conversion factor from m^3 to L
P^{cng}	Price of CNG (USD/L)
$\mathrm{NG}^{\mathrm{pty}}$	Percentage purity of methane in CNG (%)
$\mathrm{Prs}^{\mathrm{cng}}$	Pressure factor constant of CNG
P_h^{sct}	Collection cost of organic source (USD/t)
A^{cpr}	1st constant of pre-processing cost function
B^{cpr}	2nd constant of pre-processing cost function
A^{bd}	1st constant of biogas digestion cost function
B^{bd}	2nd constant of biogas digestion cost function
C^{lgd}	Drilling cost of landfill gas collection (USD)
C^{lgw}	Capital cost of gas extraction wells (USD/well)
$\mathrm{Lg}^{\mathrm{nw}}$	Number of wells
C^{lgp}	Capital cost of wellheads and pipe gathering system (USD/well)
C^{lge}	Engineering, permitting, and surveying cost (USD/well)
C^{lgOM}	Annual O&M cost (USD/y)
C^{lgf}	Flaring O&M cost (USD)
$\mathrm{CF}^{\mathrm{mhfm}}$	Conversion factor from m^3/h to ft^3/min
A^{lgc}	Capital cost constant of knockout, blower, and flare system
Af	Annualization factor
$\mathrm{CF}^{\mathrm{m3f3}}$	Conversion factor from m^3 to ft^3
E^{lg}	Energy usage of landfill gas collection and flaring works (kWh/ft^3)
C^{ect}	Cost of electricity (USD/kWh)
A^{cgt}	1st constant of gas turbine cost function
B^{cgt}	2nd constant of gas turbine cost function
C^{cgt}	Interconnection cost of gas turbine (USD)
D^{cgt}	Annual O&M gas turbine cost (USD kWh generated/y)
$\mathrm{Eff}^{\mathrm{pgte}}$	Parasitic loss efficiency (%)
A^{cchp}	1st constant of CHP gas turbine cost function
B^{cchp}	2nd constant of CHP gas turbine cost function
C^{cchp}	Interconnection cost of CHP gas turbine (USD)
D^{cchp}	Heat recovery exchanger cost (USD/kW capacity)
E^{cchp}	Gas pipeline cost (USD/ft)
$\mathrm{CF}^{\mathrm{mft}}$	Conversion factor from m to ft
$\mathrm{Dts}^{\mathrm{gchp}}$	Length of gas pipeline (m)
F^{cchp}	Steam pipeline cost (USD/ft)
$\mathrm{Dts}^{\mathrm{schp}}$	Length of steam pipeline (m)
G^{cchp}	Circulation pump cost (USD)
H^{cchp}	Annual O&M CHP gas turbine cost (USD.kWh generated/y)
C^{bfw}	Cost of boiler feed water (USD/m^3)

A^{cngp}	1st constant of biogas upgrading to natural gas cost function
B^{cngp}	2nd constant of biogas upgrading to natural gas cost function
C^{cngp}	Interconnection cost of biogas upgrading to natural gas (USD)
D^{cngp}	Pipeline cost (USD/mi)
$\mathrm{Dts}^{\mathrm{ngp}}$	Length of pipeline (km)
$\mathrm{CG}^{\mathrm{kmmi}}$	Conversion factor from km to mi
E^{cngp}	1st constant of annual O&M cost of biogas upgrading to natural gas (USD/y)
F^{cngp}	2nd constant of annual O&M cost of biogas upgrading to natural gas (USD/y)
G^{cngp}	Electricity usage biogas upgrading to natural gas works (kWh/ft^3)
A^{ccng}	CNG capital cost constant
CV^{mbf}	Calorific value of methane in Btu/ft^3 unit (Btu/ft^3)
C^{gr}	Annual O&M of CNG works (USD/GGE)
CV^{gsl}	Calorific value of GGE (Btu/GGE

Variables

$F_{h,i}^{\mathrm{spr}}$	Flow rate from source to pre-processing (t/h)
$F_{h,j}^{\mathrm{sbd}}$	Flow rate from source to biogas digester (t/h)
F_{h}^{snot}	Utilized source flow rate (t/h)
F_{i}^{pr}	Flow rate at pre-processing inlet (t/h)
$C_{i,p}^{\mathrm{pr}}$	Properties of pre-processing inlet stream (%)
F_{i}^{pp}	Flow rate of post-processed steam (t/h)
$F_{i,j}^{\mathrm{ppbd}}$	Flow rate of post-processed stream to biogas digester (t/h)
$F_{w,j}^{\mathrm{mwbd}}$	Flow rate of municipal wastewater to biogas digester (t/h)
F_{w}^{mwnot}	Unutilized municipal wastewater flow rate (t/h)
F_{j}^{bd}	Flow rate at biogas digester inlet (t/h)
$C_{j,p}^{\mathrm{bd}}$	Properties of biogas digester inlet stream (%)
F_{j}^{bdi}	Flow rate of mixed pre-processed organic, cow manure and municipal wastewater stream (t/h)
Bg	Flow rate of biogas from anaerobic digestion process (m^3/h)
$F_{k,l}^{\mathrm{lgbc}}$	Flow rate of collected landfill gas to biogas cleaning (m^3/h)
F_{k}^{lgnot}	Unutilized landfill gas flow rate (m^3/h)
F_{l}^{bc}	Flow rate at biogas cleaning inlet (m^3/h)
$C_{l,c}^{\mathrm{bc}}$	Biogas cleaning stream methane content (%)
F_{l}^{pbc}	Flow rate of cleaned biogas (m^3/h)
$F_{l,m}^{\mathrm{bcd}}$	Flow rate of cleaned biogas to demand (m^3/h)
Y_{m}^{d}	Binary variable to determine existence of the demand
$C_{m,c}^{d}$	Methane content of the supplied biogas to the demand (%)
$\mathrm{Pw}^{\mathrm{gte}}$	Power generated from gas turbine (MW)
$\mathrm{Pw}^{\mathrm{chp}}$	Power generated from CHP gas turbine (MW)
$\mathrm{Stm}^{\mathrm{chp}}$	Steam generated from CHP gas turbine (t/h)
Rev	Total annual revenue (USD/y)
$\mathrm{Rev}^{\mathrm{gte}}$	Annual revenue from generating electricity via gas turbine (USD/y)
$\mathrm{Rev}^{\mathrm{chp}}$	Annual revenue from selling electricity and steam via CHP gas turbine (USD/y)
$\mathrm{Rev}^{\mathrm{ngp}}$	Annual revenue from supplying natural gas via pipeline (USD/y)
$\mathrm{Rev}^{\mathrm{cng}}$	Annual revenue from selling CNG (USD/y)
TAC	Total TAC
$\mathrm{TAC}^{\mathrm{clt}}$	TAC of source collection and transportation cost (USD/y)
$\mathrm{TAC}^{\mathrm{pr}}$	TAC of pre-processing cost (USD/y)
$\mathrm{TAC}^{\mathrm{bd}}$	TAC of biogas digestion works (USD/y)
$\mathrm{TAC}^{\mathrm{lg}}$	TAC of landfill gas collection works (USD/y)
$\mathrm{TAC}^{\mathrm{gte}}$	TAC of gas turbine (USD/y)
$\mathrm{TAC}^{\mathrm{chp}}$	TAC of CHP gas turbine (USD/y)
$\mathrm{TAC}^{\mathrm{ngp}}$	TAC of supplying natural gas via pipeline works (USD/y)
$\mathrm{TAC}^{\mathrm{cng}}$	TAC of CNG works (USD/y

Introduction

Currently, most of the industry practices are based on the linear economy concept. The raw materials are taken from the environment for manufacturing new products, and the waste or by-products will be then discarded into the environment (United Nations Industrial Development Organization (UNIDO) 2021). An alternative (or as replacement) concept, which is known as circular economy, promotes the minimization of the use of fresh resource via the 3R (reduce, reuse, recycle) (Wu et al. 2014) or 6R (reuse, recycle, redesign, remanufacture, reduce, recover) practice (Jawahir and Bradley 2016). Additionally, the waste streams can also be used as a source of energy.

The wastes generated from foods are subject of concern. Every year, almost 30% of food produced is lost worldwide (Heller 2019). This can serve as a factor causing climate change as the food waste, if left untreated and sent to landfill, will contribute to methane emissions to the environment. Instead of leaving the waste 'as-is,' i.e. naturally degraded hence contributing to methane release into the environment, it can be processed or digested to produce biogas. There could be two ways of tapping biogas from food waste, i.e. (1) direct collection of food waste from nearby generating points, e.g. collection from households, wet markets, etc., or (2) indirectly via landfill gas (Kalantarifard and Yang 2011). The food waste and the landfill gas can be integrally processed in a centralized facility as the renewable energy generated can be supplied to the nearby industries/communities. Hence, the intended facility acts as a platform for industrial symbiosis that enables material exchange and resource recovery works.

The industrial symbiosis to be performed, from a business point of view, requires that the energy or materials exchange to be economically feasible. It has to generate profit, and the profit may be subjected to the magnitude of revenue, capital expenditure (CAPEX) and operating expenditure (OPEX) of the selected system installed. Technically, the biogas production also needs to be able to digest the sources as wastewater or organic wastes sent to the biogas may have different characteristics, which are not as homogeneous as they are sourced from an individual plant. This will open an opportunity for optimization to be implemented, maximizing the biogas production and/or maximizing the profit to be obtained (Kim et al. 2018a, b). Optimization is associated with using specific methods for determining the most cost-effective and efficient solution to a problem or design for a process (Edgar et al. 2001).

Biogas can be produced from several feedstock types, namely animal manure, e.g. cow and poultry manures, and other organic wastes, e.g. food waste and kitchen waste. Applying co-digestion, i.e. digestion with more than one feedstock has shown to improve the overall digestibility (El-Mashad and Zhang 2010). Chomette et al. (2018) has developed a MILP model to optimize the biogas plant location based on spatial locations concerning the feedstock, demands, and possible exchanges between the conversion plants. Egieya et al. (2019) has developed a model that economically optimizes biogas supply network from various types of feedstocks. It includes consideration of dry matter content and methane yield to represent real-world condition. A Mixed Integer Linear Program (MINLP) model was developed by Díaz-Trujillo and Nápoles-Rivera (2019) to optimize biogas supply chains in Mexico. It considers economic and environmental factors. The model could propose optimal selection and location of processing and purification technologies. The case study conducted shows that total annual profit can be increased and greenhouse gas (GHG) saving can be achieved.

A model proposed by Sarker et al. (2019) consists of four stages for optimization, i.e. hubs, reactors, condensers, and demand points. With an objective to minimize total cost, it is formulated as MINLP. Magli et al. (2018) conducted a techno-economic optimization of biogas plant that sources agricultural residues and maize silage as the feedstocks. The biogas produced is used for an internal combustion engine so that the plant is self-sufficient in terms of energy. Cavana and Leone (2019) developed a model that enables blending raw biogas into the Italian gas network. It considers pollutant concentration, e.g. sulphur compounds, oxygen (O_2), and siloxanes asper regulated by the national requirement. The study shows that the biogas injection into the gas network is able to reduce natural gas dependence up to 4.7%. Boldrin et al. (2016) studied the optimization of biogas production via co-digestion of sugar beet with pig slurry. Use of sugar beet improves GHG and energy balances, though it will increase cost feedstock. For medium to large biogas plants, the preferred solution suggested is the use of low shared sugar beets as co-substrate.

Pérez-Camacho et al. (2019) conducted Life Cycle Analysis (LCA) of a biogas plant in Northern Ireland, with the biogas' intended end-users are supposed to generate electricity by supplying it to the gas grid, or for transportation. The study results show that GHG can be reduced, given displacement of petrol and diesel fuels. Overall, all of the scenarios conducted can provide savings of 191 kg CO_2-eq or more. Jensen et al. (2017) has proposed a MIP model for biogas supply which considers energy and mass losses from the farmer up to the energy demand. Time scheduling of the feedstock supply is set on a weekly basis. It is emphasized by the author that profitable biogas plant can be achieved with careful planning of the complete supply chain.

Stunzenas and Kliopova (2018) have conducted a study to optimize municipal biodegradable waste (BDW). It is found that the usage of BDW to produce biogas can decrease GHG emission by 600 ton CO_2-eq annually. Resulting by-product, i.e. compost, is rich with metals, impurities and microbiological contamination, suggesting that it may be suitable for the only purpose of overlaying the landfill. Mayerle and Figueiredo (2016) proposed models for optimal bioenergy supply logistics system design. It can determine the optimal location of a biogas generation complex as the feedstocks were supplied by many small livestock farms. It considers farm locations and biomass transportation costs. Subject to the recommendation of cost–benefit analysis, collection from certain locations will be postponed to minimize biogas loss.

Othman et al. (2017) has proposed the Gas System Cascade Analysis (GASCA) framework based on Timed Based Pinch Analysis (TBPA). The results show that the downstream demands, i.e. electricity, cooking gas, and natural gas vehicle (NGV) can be met based on the determined capacities of the digesters. The case study conducted has shown that 138 t of CO_2-eq can be saved daily via the proposed method. Menna et al. (2018) have conducted a study that uses by-products from existing plants to optimize biogas production. The case study undertaken has three scenarios, i.e. business as usual (BAU), to maximize net present value (NPV), and minimize the use of land. The study concluded that the feasibility of the project depends on a variety of agro-energetic factors, e.g. feedstocks, technology solutions, transportation, and logistics. It is also shown that usage of local by-products will improve profitability and reduce footprints of current biogas chains. Dutenkefer et al. (2018) in their study, considered biogas generation as one of the sugarcane mill product portfolios. It is used as a substitution for generating electricity and diesel. It is found that only the 2nd option is economically feasible as it may heavily depend on diesel and ethanol prices factor.

A study by Salimi et al. (2021) used the restaurant food waste (RFW) as the feedstock of the proposed biorefinery. 4850 m^3 of biogas is able to be produced from 100 t of RFW. Menin et al. (2021) conducted techno-economic analysis of biomass conversion facility integrated with syngas bio methanation process. Instead of applying anaerobic digestion process, the biomethane is obtained through the gasification of biomass, mixing of the syngas with pure hydrogen, and scrubbing of the gas mixture processes combination. 0.39 Nm^3 of biogas can be obtained per dry t of biomass. Ortiz-Sanchez et al. (2021) explored the use of orange peel as the main feedstock of a biorefinery. 0.21 kg of biogas per t of orange peel is able to be produced and in terms of mass, it is considered as the best product of the biorefinery.

To the authors' best knowledge, a study that synthesizes optimal biogas production network from the combination of organic waste and landfill gas while considering downstream usage with certain economic objectives is yet to be developed. This study plans to optimize the production performance of biogas from multiple sources of waste, such as animal manures, food waste and landfill gas in a centralized facility. The objective is to obtain maximum profit from the usage of biogas to the downstream users, either in the form of heat, electricity (or both combined), purified biogas, or compressed natural gas (CNG). The following *Superstructure* and *Model Development* sections will provide elaboration on the superstructure and mathematical formulations developed.

Superstructure and model development

Subsection of *Superstructure* discusses the proposed superstructure of the study. A superstructure is a reducible structure that embeds all feasible processes and all feasible interconnections that serve as the possible candidates of the optimal design structure (Smith 2016). The mathematical formulations listings are provided in the *Mathematical Formulation* subsection.

Superstructure

The model's superstructure is given in Fig. 1as follows:

The model consists of nine (9) sets, namely the organic sources *(h)*, pre-processing section *(i)*, municipal wastewater *(w)*, biogas digester *(j)*, landfill biogas *(k)*, biogas cleaning *(l)*, end-use *(m)*, organic sources properties *(p)*, and specific methane content in the raw biogas *(c)*. The sources are the food waste from households, organic waste from wet markets, cow manure, and oil palm empty fruit bunch (EFB). Each has different *p* value as the items of interest include total solid content (TS), volatile solid content (VS), and carbon/nitrogen ratio (CNR). In general, agricultural waste has higher CNR value, while the food-based waste is relatively low in terms of the CNR content (Akunna 2019).

All organic wastes, except from the municipal wastewater, need to be collected and transported to the centralized facility. It is assumed that supply of wastewater is available near the facility with negligible connection cost. It is intended to establish the facility nearby/beside the landfill gas collection farm. Certain organic wastes must be pre-processed via hammer mill to perform size reduction as the process is applicable for the household food waste, wet market organic waste, and the EFB. The pre-processed stream is then mixed with cow manure at certain mixture ratio that considers the CNR. For example, the CNR value of the mixed stream should be the same, less than 30 and more than 20 ($20 \leq \text{CNR} \leq 30$). After that, it is mixed with municipal wastewater to ensure that the TS content before the digestion process is between 4 and 10%.

After the anaerobic digestion process, the raw biogas produced is mixed with landfill gas which is collected separately. A detailed description of the landfill gas collection and flaring step is made by the US Environmental Protection

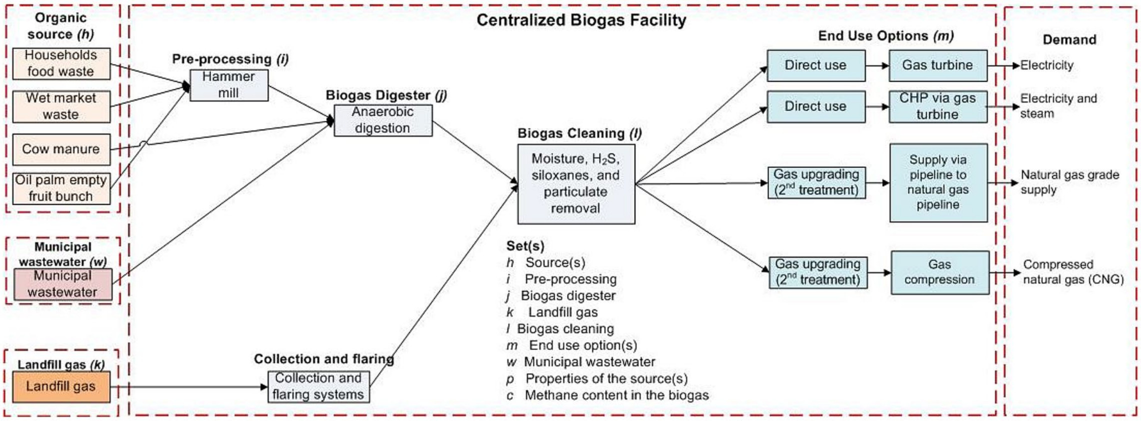

Fig. 1 Superstructure of the study

Agency (US EPA 2020a). The biogas methane content is slightly higher than the methane content of landfill gas. The mixed gas stream will be cleaned to remove moisture, hydrogen sulphide (H_2S), siloxanes compounds, and particulates. It can then be *directly used* for energy generation purposes, e.g. to generate electricity via a gas turbine or combined heat and power (CHP) via a gas turbine. A 2nd treatment is required if the gas stream is intended to be used for higher methane purity application, e.g. to be supplied as a natural gas substitute via pipeline or compressed for vehicle fuel application as compressed natural gas (CNG). Each end option has different cost magnitude, which is an item of consideration in the optimization model. Other items that involve cost are the organic waste (except municipal wastewater) collection and transportation cost, the pre-processing step, the anaerobic digestion process, the landfill gas collection and flaring works, and the biogas cleaning process. The following *Mathematical Formulation* subsection provides the list of equations used in the model.

Mathematical formulation

The main objective of the model is to obtain maximum profit (Pr) from the usage of the biogas, based on the selected end-use option. Rev^T is the total revenue generated from end usage commercial activity of the biogas. TAC is the total annual cost of the whole system.

Objective function

$$\mathrm{MaxPr} = \mathrm{Rev}^T - \mathrm{TAC} \tag{1}$$

Constraints

Sources flow rate constraints:

F^s_h is the flow rate of the source in ton per hour (t/h) unit. $F^{\mathrm{spr}}_{h,i}$ is its flow rate to the pre-processing section and $F^{\mathrm{sbd}}_{h,j}$ is its flow rate to the biogas digester. F^{snot}_h is the unutilized source. $C^s_{h,p}$ is the properties of the source as the flow rate and the properties should be in balance as Eqs. (2–3). $B^{\mathrm{spr}}_{h,i}$ and $B^{\mathrm{sbd}}_{h,i}$ are the binary parameters to limit the flow rate to the pre-processing and the biogas digester, respectively. is a relatively large value.

$$F^s_h = \sum_i F^{\mathrm{spr}}_{h,i} + \sum_j F^{\mathrm{sbd}}_{h,j} + F^{\mathrm{snot}}_h \quad \forall h \tag{2}$$

$$F^s_h \times C^s_{h,p} = \sum_i (F^{\mathrm{spr}}_{h,i} \times C^s_{h,p}) + \sum_j (F^{\mathrm{sbd}}_{h,j} \times C^s_{h,p}) + \left(F^{\mathrm{snot}}_h \times C^s_{h,p}\right) \quad \forall h, p \tag{3}$$

$$K \times B^{\mathrm{spr}}_{h,i} \geq F^{\mathrm{spr}}_{h,i} \quad \forall h, i \tag{4}$$

$$K \times B^{\mathrm{sbd}}_{h,j} \geq F^{\mathrm{sbd}}_{h,j} \quad \forall h, j \tag{5}$$

Pre-processing constraints:

Equations (6–10) provide the formulation regarding the pre-processing works. The flow rate of the pre-processing section is F^{pr}_i and the stream properties are $\mathrm{C}^{\mathrm{pr}}_{i,p}$. It is assumed that some losses will incur during the pre-processing as A^{pr}_i is the process' recovery factor constant. F^{pp}_i is the flow rate after considering the losses. The pre-processed stream will be sent to the biogas digester as $F^{\mathrm{ppbd}}_{\mathrm{i,j}}$.

$$F^{\mathrm{pr}}_i = \sum_h F^{\mathrm{spr}}_{h,i} \quad \forall i \tag{6}$$

$$F^{\mathrm{pr}}_i \times C^{\mathrm{pr}}_{i,p} = \sum_h \left(F^{\mathrm{spr}}_{h,i} \times C^s_{h,p}\right) \quad \forall i, p \tag{7}$$

$$F^{\mathrm{pr}}_i \times A^{\mathrm{pr}}_i = F^{pp}_i \quad \forall i \tag{8}$$

$$F^{pp}_i = \sum_j F^{\mathrm{ppbd}}_{i,j} \quad \forall i \tag{9}$$

$$F^{ppr}_i \times C^{\mathrm{pr}}_{i,p} = \sum_j \left(F^{\mathrm{ppbd}}_{i,j} \times C^{\mathrm{pr}}_{i,p}\right) \quad \forall i, p \tag{10}$$

Municipal wastewater constraint:

F^{mw}_w is the availability of the municipal wastewater as $F^{\mathrm{mwbd}}_{w,j}$ is the supply flow rate to the biogas digester as Eq. (11). F^{mwnot}_w is the unutilized municipal wastewater.

$$F^{\mathrm{mw}}_w = \sum_j F^{\mathrm{mwbd}}_{w,j} + F^{mwnot}_w \quad \forall w \tag{11}$$

Biogas digester constraints:

Flow rate from the source and the pre-processing combined at the biogas digester are F^{bd}_j and $C^{\mathrm{bd}}_{j,p}$, respectively. The stream's CNR value should be more or equal to 20, and less or equal to 30 as suggested by Akunna (2019). This is considered in Eq. (14). The applicability of the CNR value is only for the organic source from the *(h)* set. The CNR of the municipal wastewater in this study is not considered given its purpose is to ‘dilute’ the organic waste to a certain TS content value prior to be anaerobically digested. As such, F_j^{bd} is then mixed with municipal wastewater to ensure that TS content is between 4 and 10%. F_j^{bdi} is the mixed stream and the considerations are written as Eqs. (16–17). Multiplication of F_j^{bdi}, and its properties ($C_{j,p}^{\mathrm{bdi}}$, specifically the VS content) as well as biogas yield (Bg^{yld}) (m^3 per t VS) will result in the generation of raw biogas (Bg) in m^3/h as in Eq. (18).

$$F_j^{\mathrm{bd}} = \sum_h F_{h,j}^{\mathrm{sbd}} + \sum_i F_{i,j}^{\mathrm{ppbd}} \quad \forall j \tag{12}$$

$$F_j^{\mathrm{bd}} \times C_{j,p}^{\mathrm{bd}} = \sum_h \left(F_{h,j}^{\mathrm{sbd}} \times C_{h,p}^{s} \right) + \sum_i \left(F_{i,j}^{\mathrm{ppbd}} \times C_{i,p}^{\mathrm{pr}} \right) \quad \forall j, p \tag{13}$$

$$20 \le C_{j,p}^{\mathrm{bd}} \le 30 \quad p = CNR \tag{14}$$

$$F_j^{\mathrm{bdi}} = F_j^{\mathrm{bd}} + \sum_w F_{w,j}^{\mathrm{mwbd}} \quad \forall j \tag{15}$$

$$F_j^{\mathrm{bdi}} \times C_{j,p}^{\mathrm{bdi}} = \left(F_j^{\mathrm{bd}} \times C_{j,p}^{\mathrm{bd}} \right) + \sum_w \left(F_{w,j}^{\mathrm{mwbd}} \times C_p^{\mathrm{mw}} \right) \quad \forall j \tag{16}$$

$$0.04 \le C_{j,p}^{\mathrm{bdi}} \le 0.1 p = TS \tag{17}$$

$$\sum_j \left(F_j^{\mathrm{bdi}} \times C_{j,p}^{\mathrm{bdi}} \times Bg^{yld} \right) = Bg\, p = VS \tag{18}$$

Landfill gas constraint:

F_k^{lg} is the flow rate of the collected landfill gas in m^3/h. The value and basis reference are described in the *Case Study* section. The landfill gas flow rate to the biogas cleaning section is $F_{k,l}^{lgbc}$ and F_k^{lgnot} is the unutilized landfill gas as in Eq. (19).

$$F_k^{\mathrm{lg}} = \sum_l F_{k,l}^{lgbc} + F_k^{\mathrm{lgnot}} \quad \forall k \tag{19}$$

Biogas cleaning constraints:

The biogas cleaning section inlet will receive gas streams from the landfill gas and the biogas digester’s raw biogas combined. F_l^{bc} is the inlet gas flow rate and $C_{l,c}^{\mathrm{bc}}$ is its percentage of methane content. The cleaning process will incur some losses as H_2S, siloxanes, particulates and moisture are removed from the raw biogas. A_l^{bcl} is the gas recovery factor constant and F_l^{pbc} is the flow rate of the gas after cleaning step. It is then sent to the demand ($F_{l,m}^{\mathrm{bcd}}$). In Eq. (23), the flow rate of F_l^{pbc} should be the same as $F_{l,m}^{\mathrm{bcd}}$ and the methane content of both streams should also be balance as in Eq. (24).

$$F_l^{\mathrm{bc}} = \sum_k F_{k,l}^{lgbc} + Bg \quad \forall l \tag{20}$$

$$F_l^{\mathrm{bc}} \times C_{l,c}^{\mathrm{bc}} = \sum_k \left(F_{k,l}^{lgbc} \times C_c^{\mathrm{lg}} \right) + \left(Bg \times C_c^{ad} \right) \quad \forall l, c \tag{21}$$

$$F_l^{\mathrm{bc}} \times A_l^{bcl} = F_l^{\mathrm{pbc}} \quad \forall l \tag{22}$$

$$F_l^{\mathrm{pbc}} = \sum_m F_{l,m}^{\mathrm{bcd}} \quad \forall l \tag{23}$$

$$F_l^{\mathrm{pbc}} \times C_{l,c}^{\mathrm{bc}} = \sum_m \left(F_{l,m}^{\mathrm{bcd}} \times C_{l,c}^{\mathrm{bc}} \right) \quad \forall l, c \tag{24}$$

Demand constraints:

As per Eqs. (25–27), F_m^d is the flow rate at the demand as it will receive the gas stream from the biogas cleaning section and $C_{m,c}^d$ is the percentage of methane content. Y_m^d is the binary variable that determines the existence of each option. Equation (26) defines that at most only one will be selected. The demand’s methane mass load should be the same as the supply stream as considered in Eq. (27). There are four (4) types of demand as described earlier, which are (i) electricity generation via gas turbine, (ii) combined heat and power (CHP) via gas turbine, (iii) natural gas grade supply via pipeline, and (iv) compressed natural gas (CNG) as vehicle fuel.

$$F_m^d = Y_m^d \times \left(\sum_l F_{l,m}^{\mathrm{bcd}} \right) \quad \forall m \tag{25}$$

$$\sum_m Y_m^d \le 1 \tag{26}$$

$$F_m^d \times C_{m,c}^d = \sum_l \left(F_{l,m}^{\mathrm{bcd}} \times C_{l,c}^{\mathrm{bc}} \right) \quad \forall m \tag{27}$$

There are four types of demand in the *m* set with specific denomination as follows:

- M1: Electricity generation via gas turbine
- M2: CHP, i.e. electricity and steam generation via gas turbine
- M3: Refined biogas for supply to natural gas pipeline

- M4: CNG

Power and steam generations constraints:

Pw^{gte} is the power generated by gas turbine as presented in Eq. (28). It is obtained by multiplying with following parameter, i.e. binary parameter which enable the gas turbine option to be selected (A_m^{gte}), F_m^d, $C_{m,c}^d$, gross capacity factor (GCF), the calorific value of methane (CV^{CH4}), the electrical efficiency of gas turbine (Eff^{egte}), the parasitic load factor of gas turbine (Eff^{pgte}), and conversion factor from MW to kW (CF^{MWkW}), divided by conversion factor from hour to second (CF^{hs}).

The power generated via gas turbine (Pw^{chp}) for CHP is principally the same as Eq. (28). The amount of steam generated from heat recovery of the gas turbine is obtained through the multiplication of A_m^{chp}, Pw^{chp}, and heat recovery efficiency of gas turbine (Eff^{hchp}), divided by Eff^{echp}, Eff^{pchp}, latent heat of steam in MJ/t unit (Stm^{lh}), and CF^{MWkW} in Eq. (30).

through the pipeline (Rev^{ngp}), and selling CNG for vehicle fuel application (Rev^{cng}).

Rev^{gte} is obtained through the multiplication of Pw^{gte} with annual working hour (AWH), and selling price of electricity in USD/kWh unit. Rev^{chp} has two components, i.e. (1) selling electricity revenue stream through the multiplication of Pw^{chp} with AWH and P^{ect}, (2) selling steam revenue stream as Stm^{chp} is multiplied by AWH and selling price of steam in USD/t unit (P^{stm}).

In Eq. (34), the multiplication product of binary parameters that only enables the supplying of gas via pipeline option is selected (A_m^{ngp}) with, F_m^d, $C_{m,c}^d$, GCF, CV^{CH4}, AWH, price of natural gas in USD/million Btu (MMBtu) unit (P^{ng}), and discount factor constant of the supplied gas (DF^{ngp}), divided by conversion factor constant from MJ to MMBtu (CF^{MJmbtu}) will result to Rev^{ngp}.

Rev^{cng} will require that the binary parameters that only enable the CNG option are to be selected. A_m^{cng} is multiplied with F_m^d, $C_{m,c}^d$, GCF, conversion efficiency of the CNG process (Eff^{cng}), conversion factor from m^3 to litre (L) (CF^{m3l}), and price of CNG (P^{cng}), divided by percentage purity of methane in the CNG (NG^{pty}) and pressure factor of the CNG (Prs^{cng}) as Eq. (35).

$$Pw^{\text{gte}} = \sum_m \frac{A_m^{ge} \times Y_m^d \times F_m^d \times C_{m,c}^d \times GCF \times CV^{CH4} \times \text{Eff}^{egte} \times \text{Eff}^{pgte} \times CF^{\text{MWkW}}}{CF^{hs}}; \quad c = CH4 \tag{28}$$

$$Pw^{\text{chp}} = \sum_m \frac{A_m^{\text{chp}} \times Y_m^d \times F_m^d \times C_{m,c}^d \times GCF \times CV^{CH4} \times \text{Eff}^{echp} \times \text{Eff}^{\text{pchp}} \times CF^{\text{MWkW}}}{CF^{hs}}; \quad c = CH4 \tag{29}$$

$$Stm^{\text{chp}} = \sum_m \left(A_m^{\text{chp}} \times Y_m^d \times \frac{Pw^{\text{chp}} \times \text{Eff}^{hchp} \times CF^{hs}}{\text{Eff}^{echp} \times \text{Eff}^{\text{pchp}} \times Stm^{lh} \times CF^{\text{MWkW}}} \right) \tag{30}$$

Revenue constraints:

Total revenue generated Rev is obtained from the combination of revenue generation of selling electricity via gas turbine (Rev^{gte}), selling electricity and steam via gas turbine (Rev^{chp}), supplying purified methane as natural gas grade

$$Rev = Rev^{\text{gte}} + Rev^{chp} + Rev^{ngp} + Rev^{cng} \tag{31}$$

$$Rev^{\text{gte}} = Pw^{\text{gte}} \times AWH \times P^{ect} \tag{32}$$

$$Rev^{chp} = \left(Pw^{chp} \times AWH \times P^{ect} \right) + \left(Stm^{chp} \times AWH \times P^{stm} \right) \tag{33}$$

$$Rev^{ngp} = \sum_m \frac{A_m^{ngp} \times Y_m^d \times F_m^d \times C_{m,c}^d \times GCF \times CV^{CH4} \times AWH \times P^{ng} \times DF^{ngp}}{CF^{MJmbtu}}; \quad c = CH4 \tag{34}$$

$$Rev^{cng} = \sum_m \frac{A_m^{cng} \times Y_m^d \times F_m^d \times C_{m,c}^d \times GCF \times \text{Eff}^{cng} \times AWH \times CF^{m3l} \times P^{cng}}{NG^{pty} \times Prs^{cng}}; \quad c = CH4 \tag{35}$$

Total annual cost (TAC) constraints:

In Eq. (36), total annual cost (TAC) is obtained via summation of TAC of the organic waste collection ($\mathrm{TAC}^{\mathrm{clt}}$), TAC of the pre-processing ($\mathrm{TAC}^{\mathrm{pr}}$), TAC of the biogas digester ($\mathrm{TAC}^{\mathrm{bd}}$), TAC of the landfill gas collection ($\mathrm{TAC}^{\mathrm{lg}}$), TAC of the gas turbine ($\mathrm{TAC}^{\mathrm{gte}}$), TAC of the CHP gas turbine (TAC^{chp}), TAC of the biogas upgrading for supply as natural gas substitute (TAC^{ngp}), and TAC of biogas as CNG (TAC^{cng}).

Multiplication of utilized flow rate of sources with collection costs of the source in USD/t unit (P_h^{sct}) and AWH will result in $\mathrm{TAC}^{\mathrm{clt}}$. $\mathrm{TAC}^{\mathrm{pr}}$ is obtained through the Ax + B mode cost function development as A^{cpr} is the first (1st) constant and B^{cpr} is the second (2nd) constant of the cost function. The cost function derived mainly considers the hammer mill's capital cost, operation and maintenance, energy, and labour costs. A cost sheet is developed in Microsoft (MS) Excel to determine the cost function of the applicable process. It incorporated all of the items mentioned, and the flow rate of the pre-processing stream is plotted in a graph (at x-axis) against the resulting TAC (at y-axis). The cost function, as the supporting document, is provided in the appendices section. The basis of the cost estimation is mainly referred from Seider et al. (2016) and Sinnott and Towler (2020).

$\mathrm{TAC}^{\mathrm{bd}}$ is also made as the Ax + B equation mode. A^{cbd} is the 1st constant and B^{cbd} is the 2nd constant regarding the TAC as in Eq. (39).

$$\begin{aligned} TAC = {} & \mathrm{TAC}^{\mathrm{clt}} + \mathrm{TAC}^{\mathrm{pr}} + \mathrm{TAC}^{\mathrm{bd}} + \mathrm{TAC}^{\mathrm{lg}} \\ & + \mathrm{TAC}^{\mathrm{gte}} + \mathrm{TAC}^{chp} + \mathrm{TAC}^{ngp} + \mathrm{TAC}^{cng} \end{aligned} \tag{36}$$

$$\mathrm{TAC}^{\mathrm{clt}} = \sum_h ((F_h^s - F_h^{\mathrm{snot}}) \times P_h^{\mathrm{sct}} \times AWH) \tag{37}$$

$$\mathrm{TAC}^{\mathrm{pr}} = \sum_i \left(\left(A^{cpr} \times F_i^{\mathrm{pr}}\right) + B^{cpr} \right) \tag{38}$$

$$\mathrm{TAC}^{\mathrm{bd}} = \sum_j \left(\left(A^{cbd} \times F_j^{\mathrm{bdi}}\right) + B^{cbd} \right) \tag{39}$$

To estimate $\mathrm{TAC}^{\mathrm{lg}}$, $\mathrm{TAC}^{\mathrm{gte}}$, TAC^{chp}, TAC^{ngp}, and TAC^{cng}, the main reference is obtained from US EPA (2020b). Formulation for $\mathrm{TAC}^{\mathrm{lg}}$ is made as Eq. (40). C^{lgd} is the cost of drilling and pipe crew mobilization. C^{lgw} is the capital cost of vertical gas extraction in USD/well unit and Lg^{nw} is the number of well. C^{lgp} is the capital cost of wellheads and pipe gathering system in USD/well unit, and C^{lge} is the engineering, permitting, and surveying cost as the unit is the same as the former. C^{lgOM} is the annual operating and maintenance (O&M) cost excluding electricity and C^{lgf} is the O&M cost for the flaring system. Af is the annualization factor. CF^{mhfm} is the conversion factor from m^3/h to ft^3/min as A^{lgc} is a constant value pertaining knockout, blower, and flare system cost.

The annualized cost method is an alternative to the payback period calculation method to gauge economic feasibility of the proposed projects (Sinnott and Towler 2020). Payback period may not be used to determine the overall economics of the proposed project given the fact that it does not consider the operational period of the proposed solution after the payback period (Seider et al. 2016).

$$\begin{aligned} \mathrm{TAC}^{\mathrm{lg}} = \sum_k & (((C^{lgd} + (C^{lgw} \times Lg^{nw}) + (C^{lgp} \times Lg^{nw}) \\ & + (C^{lge} \times Lg^{nw}) + (C^{lgOM} \times Lg^{nw}) + C^{lgf} \\ & + \Big(\Big(\Big(\left(F_{k,j}^{lgbc} \times CF^{mhfm}\right)^{0.61} \Big) \times A^{lgc} \Big) \Big) \times Af \Big) \\ & + \Big(F_k^{lgbc} \times AWH \times CF^{m3f3} \times E^{\mathrm{lg}} \times C^{ect} \Big) \Big) \end{aligned} \tag{40}$$

$\mathrm{TAC}^{\mathrm{gte}}$ formulation is shown in Eq. (41). A^{cgt} is the first (1st) constant regarding the TAC. B^{cgt} is the second (2nd) constant and C^{cgt} is the interconnection cost. D^{cgt} is a constant regarding O&M cost of the gas turbine.

$$\begin{aligned} \mathrm{TAC}^{\mathrm{gte}} = \sum_m A_m^{gt} \times Y_m^d \times & ((((Pw^{gt} \times A^{cgt}) \\ & - \Big(B^{cgt} \times \Big(\left(Pw^{gt}\right)^2 \Big) \Big) + C^{cgt} \Big) \times Af \Big) \\ & + \left(\frac{Pw^{gt} \times AWH \times D^{cgt}}{\mathrm{Eff}^{pgte}} \right) \Big) \end{aligned} \tag{41}$$

Equation (42) expresses the formulation for TAC^{chp}. A^{cchp} is the first (1st) constant regarding the TAC. B^{cchp} is the second (2nd) constant and C^{cchp} is the interconnection cost. D^{cchp} is a constant value regarding heat exchangers cost and E^{cchp} is a constant pertaining to gas pipeline. CF^{mft} is the conversion factor from m to ft and Dts^{gchp} is the distance of the CHP placed from the gas supply location. F^{cchp} is a constant representing steam pipelines, and Dts^{schp} is the distance between the CHP place and the demand that uses the supplied steam. G^{cchp} is a cost constant of circulation pump. H^{cchp} is constant of annual O&M and C^{bfw} is the cost of boiler feed water in USD/m^3.

$$\begin{aligned} \mathrm{TAC}^{chp} = \sum_m A_m^{chp} \times Y_m^d \times & (((((A^{cchp} \times Pw^{chp}) - \left(B^{cchp} \times \left(Pw^{chp}\right)^2\right)) \\ & + C^{cchp} + (D^{cchp} \times Pw^{chp}) + (E^{cchp} \times CF^{mft} \times Dts^{gchp}) \\ & + (F^{cchp} \times CF^{mft} \times Dts^{schp}) + G^{cchp}) \times Af) \\ & + \left(H^{cchp} \times \frac{Pw^{chp} \times AWH}{\mathrm{Eff}^{pchp}} \right) + (C^{bfw} \times Stm^{chp} \times AWH) \Big) \end{aligned} \tag{42}$$

TAC^{ngp} formulation is as in Eq. (43). A^{cngp} is the first (1st) constant value as e means the exponent. In the model,

e is put as the Euler's number i.e. 2.718. B^{cngp} is the second (2nd) constant value. C^{cngp} is a constant representing the cost of interconnection equipment. D^{cngp} is a constant value representing the pipeline cost and Dts^{ngp} is purified biogas pipeline cost. CG^{kmml} is the conversion factor from km to mile (mi). E^{cngp} and F^{cngp} are both the constants regarding O&M cost of the system excluding electricity. G^{cngp} is a constant regarding the electricity usage of the system and CF^{m3f3} is the conversion factor from m^3 to ft^3. Price of electricity is coded as C^{ect} in USD/kWh unit.

$$\begin{aligned}\mathrm{TAC}^{ngp} = \sum_m A_m^{ngp} \times Y_m^d \times \Big(\Big(\Big(\Big(A^{cngp} \times e^{\left(B^{cngp} \times F_m^d \times CF^{mhsm}\right)}\Big) \\ + C^{cngp} + \left(D^{cngp} \times Dts^{ngp} \times CG^{kmmi}\right)\Big)\Big) \times Af\Big) \\ + \left(\left(E^{cngp} \times F_m^d \times CF^{mhsm}\right) + F^{cngp}\right) \\ + \left(G^{cngp} \times F_m^d \times CF^{m3f3} \times AWH \times C^{ect}\right)\Big)\end{aligned} \tag{43}$$

The formulation for TAC^{cng} is shown as in Eq. (44). A^{ccng} is the first (1st) constant value, and CV^{mbf} is the calorific value of methane in Btu/ft^3 unit. Eff^{cng} is the process conversion efficiency and C^{gr} is the O&M cost constant of the system. CV^{gsl} is the energy content of gasoline gallon equivalent.

$$\begin{aligned}\mathrm{TAC}^{cng} = \sum_m A_m^{cng} \times Y_m^d \times \Big(\Big(\Big(A^{ccng} \times \Big(\left(F_m^d \times CF^{mhsm}\right)^{0.6}\Big)\Big) \times Af\Big) \\ + \left(\frac{F_m^d \times CF^{m3f3} \times AWH \times CV^{mbf} \times C_c^{\lg} \times \mathrm{Eff}^{cng} \times C^{gr}}{CV^{gsl}}\right)\Big)\end{aligned} \tag{44}$$

Case study

The type of sources, its properties, and collection and transportation cost are provided in Table 1. Table 2 shows the biogas types, its amount, and percentage content of methane. Other parameters are provided in Appendices section.

Table 2 Types of biogas, its amount and percentage content of methane

Type of biogas	Amount (m^3/h)	Percentage content of methane (%)
Raw biogas from anaerobic digestion	Subject to the optimization solutions	65
Landfill gas	4890	55 (Noor et al. 2013)

The food waste amount is based on the collection from 200,000 houses, and the wet market waste amount is based on the amount of wet markets located in Johor Bahru area. Cow manure availability is referred from the cow numbers in the district as well (Johor Veterinary Service Department 2017). The food waste collection is based on the municipal solid waste collection service cost performed by the contractors (PEMANDU 2015). However, for other three (3) sources, there is no specific collection cost incurred.

Results and discussion

The model is formulated as the mixed-integer non-linear program (MINLP) model. It has 9 sets, 84 parameters (including 6 binary parameters), and 38 variables (including 1 binary variable). The model is run via the Generic Algorithm Modelling Software (GAMS) version 24.7.4 in a computer with a processor capacity of IntelCore i3-8130U CPU 2.2 GHz. BARON solver is used given its capability to navigate to the global solution. An optimal solution was obtained in less than 60 s with a 1000 s time limit (reslim = 1000). The optimized solution is shown in Fig. 2 as follows:

From Fig. 2, the households food waste and the wet market waste are all utilized to produce biogas. 8.5 t/h of EFB is pre-processed. The pre-processed stream, at amount of 15.8 t/h, is then mixed with 2 t/h of cow manure and 52.8 t/h of municipal wastewater to produce 2771 m^3/h of raw biogas.

Table 1 Type of sources and its amount, properties and collection and transportation cost

Source(s)	Amount (t/h)	TS (%)	VS (%)	CNR	Collection and transportation cost (USD/t)
Food waste	5.9 (Chien Bong et al. 2017)	27.7 (Bank et al. 2011)	24.4 (Bank et al. 2011)	15 (Akunna 2019)	26.5 (PEMANDU 2015)
Wet market organic waste	2.3 (Tweib et al. 2011)	46.3 (Tweib et al. 2011)	32.4 (Tweib et al. 2011)	14 (Akunna 2019)	10.0 (PEMANDU 2015)
Cow manure	2.0 (Johor Veterinary Service Department 2017)	30.6 (Kim et al. 2018a, b)	25.7 (Kim et al. 2018a, b)	26 (Kim et al. 2018a, b)	10.0 (PEMANDU 2015)
EFB	12.0*	46.9 (Purnomo et al. 2018)	44.0 (Purnomo et al. 2018)	48 (Purnomo et al. 2018)	15.0 (PEMANDU 2015)

*Based on an oil palm mill capacity of processing sixty (60) ton of fresh fruit bunches (FFB) in one (1) hour

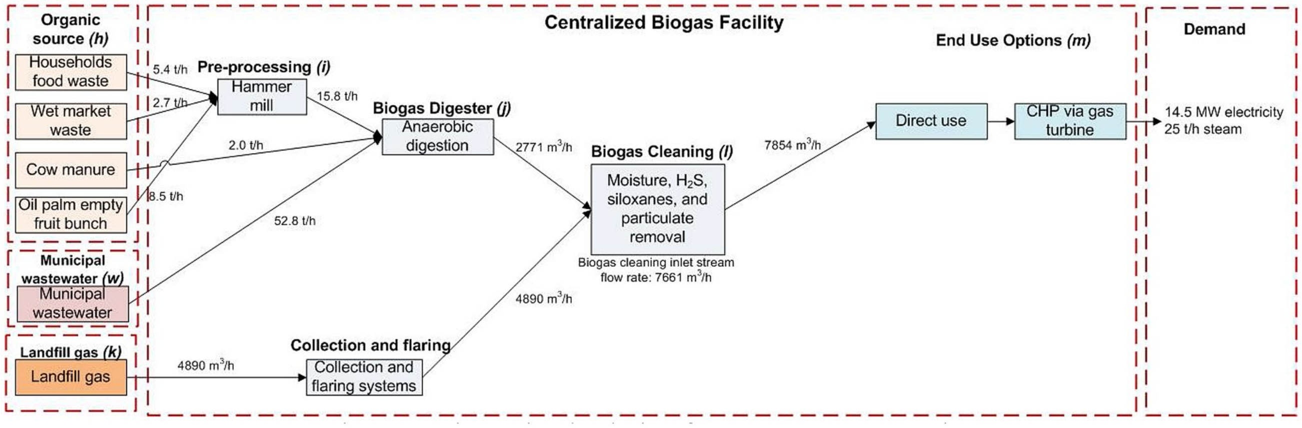

Fig. 2 The optimal solution from GAMS computation

Table 3 Breakdown of the TAC

No.	Items	Annual cost (USD/y)	Percentage from total TAC (%)
1	Organic waste collection	2,542,316	32
2	Pre-processing	1,481,467	19
3	Biogas digester operation	300,696	4
4	Landfill gas collection	491,684	6
5	Biogas cleaning + CHP gas turbine	3,157,577	40
Total			100

Table 4 List of profit generated from each end-use option

No.	End-use option(s)	Profit (USD/y)	Percentage from the best end-use option (%)
1	CHP via gas turbine	7,321,789	100
2	Selling electricity via gas turbine	3,816,178	52
3	Supplying purified methane to industry via pipeline	1,721,719	24
4	CNG as vehicle fuel	3,468,664	47

The raw biogas is then mixed with the 4890 m^3/h landfill gas to produce a cleaned biogas at 7854 m^3/h flow rate, based on the biogas cleaning inlet stream flow rate of 7661 m^3/h. The cleaned gas supply is able to generate 14.5 MW of electricity and 25 t/h of steam via CHP gas turbine. An annual profit of 7,321,789 USD/y is obtained as the annual revenue is 15,295,529 USD/y and the TAC is 7,973,740 USD/y. A breakdown of the TAC component is shown in Table 3.

From Table 3, biogas cleaning + CHP gas turbine cost provides the most significant portion of the TAC, followed by the collection of organic waste, pre-processing, landfill gas collection and biogas digester operation. The associated cost pertaining biogas production from the organic waste is roughly 54% of the total TAC, while the landfill gas collection is roughly nine (9) times lower than that. Ironically, the landfill gas amount is roughly twice than the former. This indicates that the production cost of raw biogas from anaerobic digestion of organic waste (in USD/m^3 raw biogas) is relatively higher than the latter.

As the CHP gas turbine is selected as the best option, the profits from other options are tabulated in comparison with the former as in Table 4. The profit of other options is obtained by putting Y_m^d value to 1 for specific option. For example, if the selling electricity only via gas turbine intended is to be selected, the Y_m^d value is set as Y_{M1}^d. The same concept goes for the third and fourth option i.e.Y_{M3}^d and Y_{M4}^d, respectively.

Using exchange rate of USD 1 to MYR 4, the cost of food waste collection and transportation is set at 26.50 USD/t according to the Malaysian Performance Management and Delivery Unit (PEMANDU 2015). Including the pre-processing cost, which is set at 5 t/h pre-processing capacity, the unit cost increases to 40.5 USD/t. This is equal to 162 MYR/t based on the Malaysian currency value. The food waste is all used for the CHP via gas turbine demand option as mentioned earlier. However, it is not used for other type of demand as listed in Table 4. This may suggest that for other demand option, except CHP, the food waste unit cost needs to be reduced to be economically feasible. Alternatively, instead of collecting the food waste from the household stage, the food waste can be aggregated and/or collected at the landfill site with additional labour cost to do such works need to be considered; but this comes with trade-off by minimizing the specific collection and transportation cost.

To maintain CNR value between 20 and 30, the organic wastes have to be co-digested with EFB. The former has relatively lower CNR value and the latter has a relatively higher CNR value. The co-digestion practice is common nowadays as reported in the literature. Instead of using freshwater, municipal wastewater is suggested as an alternative as it may not require specific cost compared to the latter. In the Malaysian case, the cost of freshwater is roughly 0.75 USD/m^3. If usage of freshwater is considered, an additional cost of 316,764 USD/y is anticipated.

The amount of landfill gas is obtained through formulation derived from the Intergovernmental Panel on Climate Change (IPCC 2019). This may differ from other findings, for example, by Kalantarifard and Yang (2012). They estimated, through the usage of LANDGEM software that the amount of methane available from the same site is between 0.44 and 4.52 Gg/y. If these values are translated into an hourly basis, the range is between 108 and 1105 m^3/h. If the project is to be further considered, a detailed calculation or estimation of the methane availability is suggested, using the specific data gathered from the site. Plus, there is also a need to verify the potential reduction of landfill gas production if the food waste is directly collected at the household level instead of being disposed into the landfill.

The main idea of this study is to explore the possibilities of tapping and producing biogas from multiple organic sources and landfill simultaneously, while considering the necessary techno-economic items, which include the properties of the organic sources, the methane content of the biogas produced from the CSTR and the landfill, the process yield and incurring cost of each end-use options, the organic sources' cost of collection and transportation, and the pre-processing, anaerobic digestion, and landfill gas collection cost each through the mathematical modelling approach.

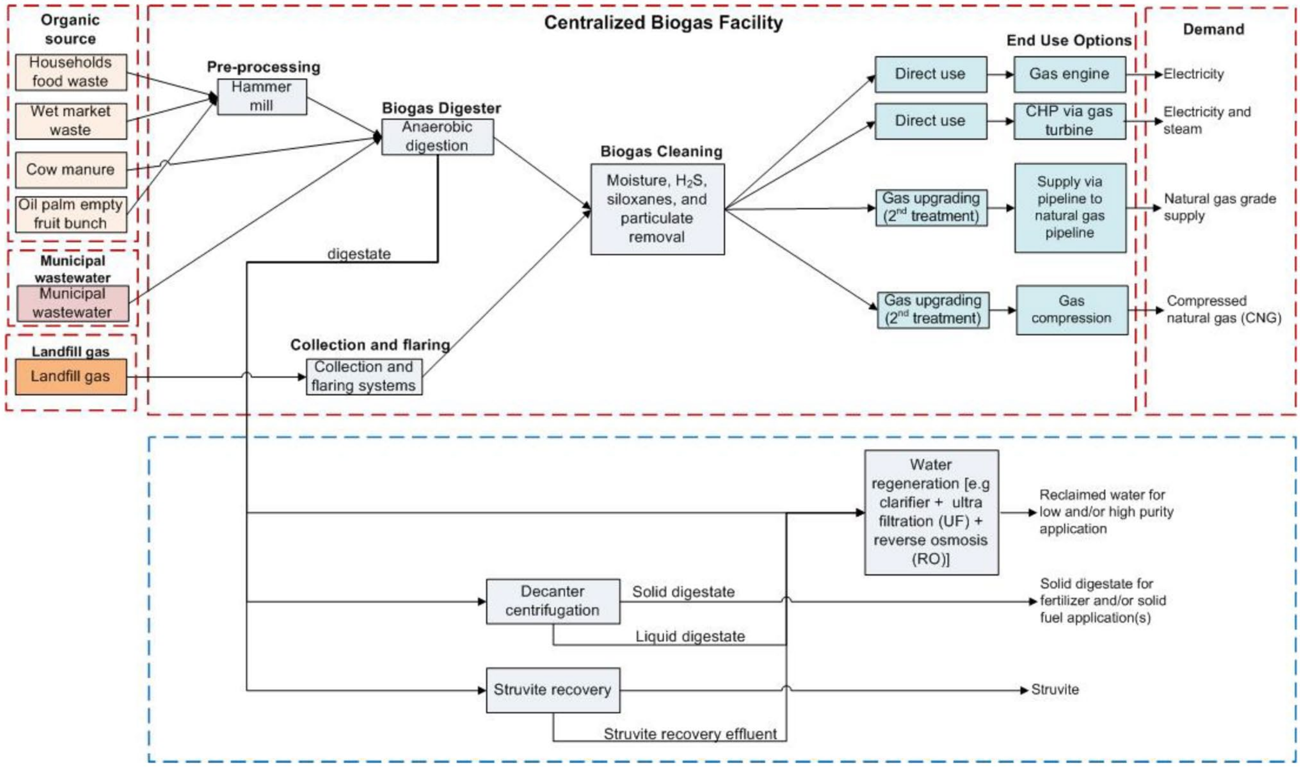

Fig. 3 The potential extension of the study as highlighted in the blue line

Applying the model in an optimization software provides the best case possible (i.e. the most profitable option), which enables the economics of the proposed project to be assessed. The features mentioned are suggested to be novel, as this study also gives certain important perspectives. For example, the use of food waste for biogas production, even though is highly recommended, may dependent on the collection and transportation cost, which may not be relatively cheap. A proposal to develop a combined biogas facility from the landfill and from the organic sources is possible with a sound economic performance. The study is in-line with journal's scope as it applies mathematical and computer-based methods and model for designing renewable energy solution that the waste is repurposed for beneficial uses.

This study has certain limitations. It does not consider the reclamation or reuse of the digestate of the anaerobic digestion process. The digestate can be considered for (1) centrifugation step to obtain two separate streams, namely the solid digestate and the liquid digestate, (2) recovery of phosphorus (P) and nitrogen (N) from the stream, or (3) regeneration as the permeate can be reused for irrigation or higher purity water application, such as boiler feed water or process water. During the anaerobic digestion process, P and N are not utilized in the fermentation pathway. Both remain in the effluent stream. As P is not a renewable source, which it is estimated that it will be depleted by the end of this century (Cooper et al. 2011). Recovery of it via struvite precipitation or chemical precipitation is advocated, although certain cost magnitude needs to be considered. Figure 3 illustrates the potential area of the next study. A study to assess the proposed project's performance considering uncertainty and in a dynamic mode is also suggested to be explored.

Conclusion

A mathematical model to optimize biogas production from the organic wastes and landfill gas combined is developed. The model considers the organic wastes properties and its collection, transportation, and pre-processing costs. Location of the centralized facility is intended to be nearby or beside the landfill gas collection farm. The combined raw biogas is cleaned before directly used to generate electricity or steam. If needed, second treatment will be required for natural gas substitute supply via pipeline or CNG. 14.5 MW of electricity and 25 t/h of steam can be generated, though the digestate can be chemically precipitated to recover struvite or regenerated to reclaim water or recover solid digestate. All options mentioned can provide additional revenue streams while minimizing fresh resource consumptions. The organic waste collection, transportation, and pre-processing cost are the subjects of attention if the biogas production from organic wastes is aspired to be feasible. However, the amount of landfill gas alone could be sufficient to show the potential of tapping the methane from the waste sectors. The model is a high level techno-economic model, which acts as a starting point for further assessment. This includes the consideration of certain uncertain items such as the seasonality, feedstock availability throughout the year, the fluctuation of demand from the end-users (if the end product selected is highly dependent on user's consumption e.g. steam and CNG; however, selling electricity to the national grid may possess very minimal fluctuation). The consideration storage area/tank is also suggested in the next study given that the supply of feedstock may be in batch mode, e.g. the EFB is sent to the facility in the daylight which necessitates a sufficient space of storage area. Further study extensions include the energy-water-waste integration and localization of some cost elements, as it may vary depending on different countries. As the bottom line, the result provides insights into the practicality of producing useable biogas from organic waste and landfill source in a relatively large scale facility, at the district level.

Appendix

See Tables 5, 6.

Landfill gas availability calculation:

$$F_k^{\mathrm{lg}} = \sum \frac{MSW \times MCF \times DOC \times DOCF \times Y \times CF^{tkg} \times \mathrm{Eff}^{\mathrm{lg}}}{CF^{dh} \times CH4^{dty} \times CH4^{pct}} \tag{45}$$

Table 5 Pre-processing section parameters

Parameters	Value
Pre-processing process' recovery factor constant, A^{pr}	95%

Table 6 Biogas digester parameters

Parameters	Value
Biogas production yield, Bg^{yld}	450 m^3/t VS

The symbols definition and the associated values are provided in Table 7 follows:

Using the values above, flow rate of the collected landfill gas is 4890 m^3/h (Tables 8, 9, 10, 11).

Table 7 Other parameters used to determine the amount of landfill gas

Parameters	Value	Reference(s)
Total waste disposed into the landfill, MSW	350 t/d	Kalantarifard and Yang (2011)
Conversion factor from t to giga gram (Gg), CF^{tGg}	0.001 t/Gg	
Methane correction factor, MCF	1	
Degradable organic carbon percentage, DOC	27.7%	Tchnobanoglous et al. (2014)
Disseminatable degradable organic carbon under anaerobic conditions, DOCF	77%	Tan et al. (2014)
Molecular weight ratio of CH_4/C, Y	1.33	IPCC (2019)
Landfill gas collection efficiency, Eff^{lg}	75%	
Conversion factor from d to h, CF^{dh}	24 h/d	
Conversion factor from t to kg, CF^{tkg}	1000 kg/t	
Density of methane, $CH4^{dty}$	0.637 kg/m^3	

Table 8 Biogas cleaning parameters

Parameters	Value
Gas recovery factor constant, A^{bcl}	99%

Table 9 Power and steam generations parameters

Parameters	Value	Reference(s)
Binary parameters that only enables the gas turbine option is to be selected, A_m^{gte}	M1: 1, M2: 0, M3: 0, M4: 0	
Gross capacity factor, GCF	93%	US EPA (2020a; b)
Calorific value of methane, CV^{CH4}	39.8 MJ/m^3	
Electrical efficiency of gas turbine, Eff^{egt}	36%	IEA (2010)
Parasitic loss efficiency of gas turbine, Eff^{pgt}	88%	US EPA (2020a; b)
Conversion factor from MW to kW, CF^{MWkW}	1000 kW/MW	
Conversion factor from hour to second, CF^{hs}	3600 s/h	
Binary parameters that only enables the gas turbine CHP option is to be selected, A_m^{chp}	M1: 0, M2: 1, M3: 0, M4: 0	
Electrical efficiency of CHP gas turbine, Eff^{echp}	36%	IEA (2010)
Parasitic loss efficiency of CHP gas turbine, Eff^{pchp}	88%	US EPA (2020a; b)
Heat recovery efficiency of gas turbine, Eff^{hchp}	40%	IEA (2010)
Latent heat of steam, Stm^{lh}	2700 MJ/t	

Table 10 Revenue parameters

Parameters	Value	Reference(s)
Annual working hour, AWH	8000 h/y	
Selling price of electricity, P^{ect}	0.08875 USD/kWh	
Selling price of steam, P^{stm}	80 USD/t	
Binary parameters that only enable the natural gas supply via pipeline option is to be selected, A_m^{ngp}	M1: 0, M2: 0, M3: 1, M4: 0	
Selling price of natural gas, P^{ng}	8.4 USD/MMBtu	Gas Malaysia Berhad (2020)
Discount factor constant of supplying natural gas via pipeline, DF^{ngp}	90%	
Binary parameters that only enable the CNG option is to be selected, A_m^{cng}	M1: 0, M2: 0, M3: 0, M4: 1	
Process conversion efficiency of CNG, Eff^{cng}	65%	US EPA (2020a; b)
Conversion factor from m^3 to litre (L), CF^{m3l}	1000 L/m^3	
Selling price of CNG, P^{cng}	0.17 USD/L	
Purity of methane in the CNG, NG^{pty}	97%	
Pressure factor of the CNG, Prs^{cng}	250	

Table 11 TAC parameters

Parameters	Value	Reference(s)
1st constant of pre-processing cos function, A^{cpr}	80,042	
2nd constant of pre-processing cost function, B^{cpr}	150,958	
1st constant of biogas digester cos function, A^{cbd}	2,003	
2nd constant of biogas digester cost function, B^{cbd}	159,313	
Annualization factor, Af	0.05	
Cost of drilling and pipe crew mobilization, C^{lgd}	20,000 USD	US EPA (2020a, b)
Capital cost of vertical gas extraction, C^{lgw}	4,675 USD/well	US EPA (2020a, b)
Number of wells, Lg^{nw}	13 (based on well number is one per acre)	
Capital cost of wellheads and pipe gathering system, C^{lgp}	17,000 USD/$\mathrm{Lg}^{\mathrm{nw}}$	US EPA (2020a, b)
Engineering, permitting, and surveying cost, C^{lge}	700 USD/$\mathrm{Lg}^{\mathrm{nw}}$	US EPA (2020a, b)
Constant of annual operating and maintenance (O&M) cost excluding electricity, C^{lgOM}	2,600 USD/$\mathrm{Lg}^{\mathrm{nw}}$	US EPA (2020a, b)
O&M cost for the flaring system, C^{lgf}	USD 5,100	US EPA (2020a, b)
Conversion factor from m^3/h to ft^3/min, CF^{mhfm}	0.59 [(ft^3/min)/(m^3/h)]	US EPA (2020a, b)
Constant value of landfill gas collection and flaring system cost, A^{lgc}	USD 4,600	US EPA (2020a, b)
1st constant regarding the gas turbine TAC, A^{cge}	2,340 USD/kW capacity	US EPA (2020a, b)
2nd constant regarding the gas turbine TAC, B^{cge}	USD 1,100,000	US EPA (2020a, b)
Interconnection cost of gas engine, C^{cge}	USD 250,000	US EPA (2020a, b)
Cost constant regarding O&M cost of the gas engine, D^{cge}	0.025 kWh generated/y (before parasitic use)	US EPA (2020a, b)
1st constant regarding the gas turbine CHP TAC, A^{cchp}	USD 2,340	US EPA (2020a, b)
2nd constant regarding the gas turbine CHP TAC, B^{cchp}	0.103	US EPA (2020a, b)
Interconnection cost of gas turbine CHP, C^{cchp}	USD 250,000	US EPA (2020a, b)
Cost constant value regarding heat exchangers cost, D^{cchp}	355 USD/kW heat recovered	US EPA (2020a, b)
Cost constant pertains to gas pipeline, E^{cchp}	63 USD/ft	US EPA (2020a, b)
Conversion factor from m to ft, CF^{mft}	3.28 ft/m	
Distance of the CHP place from the gas supply location, $\mathrm{Dts}^{\mathrm{gchp}}$	500 m	
Cost constant regarding steam pipelines, F^{cchp}	106 USD/ft	US EPA (2020a, b)
Distance between the CHP place and the demand that uses the supplied steam, Dts^{schp}	2,000 m	
Cost constant of circulation pump, G^{cchp}	USD 12,000	US EPA (2020a, b)
Cost constant of annual O&M, H^{cchp}	0.0144 USD/kWh generated/y (before parasitic use)	US EPA (2020a, b)
Cost of boiler feed water, $\mathrm{C}^{\mathrm{bfw}}$	1.50 USD/m^3	Sinnott and Towler (2020)
1st constant value of supplying natural gas via pipeline TAC, A^{cngp}	USD 6,000,000	US EPA (2020a, b)
Exponent, e	2.718	
2nd constant value of supplying natural gas via pipeline TAC, B^{cngp}	0.0003	US EPA (2020a, b)
Cost constant regarding the cost of interconnection equipment, C^{cngp}	USD 400,000	US EPA (2020a, b)
Cost constant regarding the pipeline cost, D^{cngp}	1,000,000 USD/mi pipeline	US EPA (2020a, b)
Purified biogas pipeline length to the demand, Dts^{ngp}	15 km	
Conversion factor from km to mile (mi), CG^{kmml}	1.6 km/mi	
1st constant regarding O&M cost of the system excluding electricity, E^{cngp}	250	US EPA (2020a, b)
2nd constant regarding O&M cost of the system excluding electricity, F^{cngp}	148,000	US EPA (2020a, b)
Cost constant regarding the electricity usage of the system, G^{cngp}	0.009 kWh/ft^3 biogas inlet	US EPA (2020a, b)

Table 11 (continued)

Parameters	Value	Reference(s)
Conversion factor from m^3 to ft^3, CF^{m3f3}	35.3 ft^3/m^3	US EPA (2020a, b)
Price of electricity, C^{ect}	0.08425 USD/kWh	
1st constant value of CNG TAC, A^{ccng}	95,000	US EPA (2020a, b)
Calorific value of methane, CV^{mbf}	39.8 MJ/m^3	
CNG process conversion efficiency, Eff^{cng}	65%	US EPA (2020a, b)
O&M cost constant of the CNG system, C^{gr}	1 USD/gasoline gallon equivalent (GGE)	US EPA (2020a, b)
Energy content of gasoline gallon equivalent, CV^{gsl}	111,200 Btu/GGE	US EPA (2020a, b)

Cost curve of pre-processing TAC

See Fig. 4.

Cost function: $Y = 80{,}042x + 150{,}958$; Y = Total annual cost (USD/y); x = Flow rate of organic source supply (t/h).

$R^2 = 1$

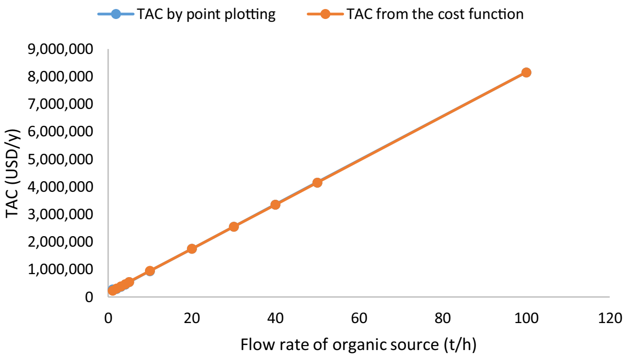

Fig. 4 Pre-processing TAC Cost Curve

Cost curve of pre-processing TAC

See Fig. 5.

Cost function: $Y = 2003x + 159{,}313$; Y = Total annual cost (USD/y); x = Flow rate of stream (m^3/h).

$R^2 = 1$.

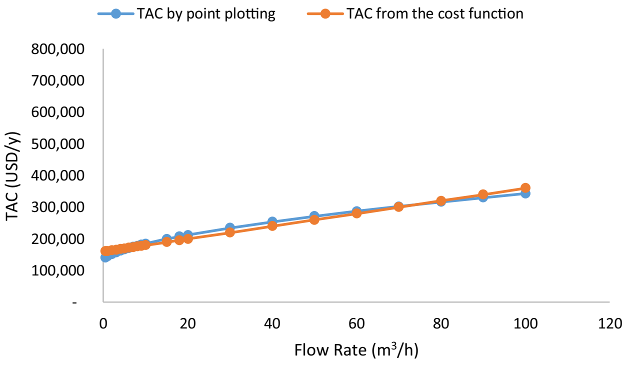

Fig. 5 Biogas TAC Cost Curve

Author contributions MAM was involved in conceptualization, methodology, software, writing—original draft, visualization, and formal analysis. SRWA was involved in conceptualization, methodology, validation, resources, supervision, and funding acquisition. JSL was involved in methodology, validation, supervision, and funding acquisition. ZAM was involved in supervision and resources.

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Authors and Affiliations

Mohd Arif Misrol[1] · Sharifah Rafidah Wan Alwi[1] · Jeng Shiun Lim[1] · Zainuddin Abd Manan[1]

✉ Sharifah Rafidah Wan Alwi
syarifah@utm.my

[1] Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment (RISE), School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Block N29, 106-02, 81310 UTM Johor Bahru, Johor, Malaysia