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Process Systems Engineering and Process Safety

Multi-objective optimization of methane production system from biomass through anaerobic digestion

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Abstract: This work addressed the multi-objective optimization of a biogas production system considering both environmental and economic criteria. A mixed integer non-linear programming (MINLP) model was established and solved with non-dominated sorting genetic algorithm II, from which the Pareto fronts, the optimal technology combinations and operation conditions were obtained and analyzed. It's found that the system is feasible in both environmental and economic considerations after optimization. The most expensive processing section is decarbonization; the most expensive equipment is anaerobic digester; the most power-consuming processing section is digestion, followed by decarbonization and waste management. The positive green degree value on the process is attributed to processing section of digestion and waste management. 3:1 chicken feces and corn straw, solar energy, pressure swing adsorption and 3:1 chicken feces and rice straw, solar energy, pressure

swing adsorption are turned out to be two robust technology combinations under different prices of methane and electricity by sensitivity analysis. The optimization results provide support for optimal design and operation of biogas production system considering environmental and economic objectives.

Keywords: Biogas production system; MINLP; Multi-objective optimization; non-dominated sorting genetic algorithm II ; Green degree value

Abbreviations

BRI	briquette
CHO	chop
DGR	digester
SC	solar collector
BB	biomass boiler
AGT	agitator
PM1	pump1
PM2	pump2
PM3	pump3
DES	desulfurization
DEH	dehumidification
ADS	adsorber
DES	desorber
CP1	compressor1
CP2	compressor2

SCP	screw press
SLP	slurry pool
MBR	Membranes
SF	solid filter
DRY	Dryer
CT	collection & transportation
PRE	Pretreatment
DGN	Digestion
DEC	Decarbonization
WM	waste management

1 Introduction

Due to the depletion of fossil fuel and the environmental problems associated with fossil energy, considerable effort has been made to search for alternative energy [1-2]. Biogas produced via anaerobic digestion of livestock and crop straw has attracted worldwide interest as it is clean and renewable energy [1,3]. The produced biogas is generally utilized for the production of electricity, heat, vehicle fuel [4] and natural gas substitute after purification, and the digestate byproduct can be employed as fertilizer after treatment. A typical biogas production system includes the processing section of biomass collection and transportation, pretreatment, anaerobic digestion, biogas cleaning and decarbonization, and waste management. In addition, there are a variety of options for feedstocks, digestion heat supply technologies and biogas decarbonization technologies. Thus, it's difficult to obtain the optimal flowsheet and section combination for a biogas production system only by simple calculation and empirical analysis.

Considerable efforts have been made to evaluate and optimize the individual processing sections of a biogas production system. For example, Yu et al. [5,6] improved a site selection and biomass delivery model, and make it suitable for many types of biomass and road delivery. Singh et al. [7] developed a mathematical model for collecting and transporting biomass from fields to the power plant. The model was used to calculate the unit transportation cost, and found that the unit cost decreases as the transportation distance increases. Ariunbaatar et al. [8] compared factors like efficiency, environmental sustainability, capital and operational costs of different pretreatment pathways, and found that the process with thermal pretreatment at low temperature with two stages digestion presents the best economic performance. Mendes et al. [9] used ADM1 model to investigate the variation of biogas yield and biogas composition with changing digestion time. Wu et al. [10] established two-column six-step pressure swing adsorption simulation model for biogas decarbonization. It was found that the processes with MOF-508b and CMS-3K as adsorbents can decrease the energy consumption by 56% and 50%, respectively, compared with the Zeolite 13X absorbent. Rehl et al. [11] conducted Life Cycle Assessment (LCA) to compare the energy efficiency and environmental impact of different biogas digestate treatment alternatives. The belt dryer is turned out to be the option with highest primary energy demand, Global Warming Potential (GWP) and acidification potential (AP) among the compared options. The solar dryer has the lowest environmental impact.

Furthermore, for comprehensive assessment of the biogas production system, Wu et al. [12] established energy models for each processing section and evaluated the energy efficiency of the system in 32 scenarios (2 digestion technologies alternatives, 4 decarbonization technology alternatives, 2 heat supply methods, and 2 waste heat

recovery options). In addition, they conducted energetic-environmental-economic assessment of a typical biogas production system with three utilization pathways (CPH, bio-methane and fuel cell) [13].

The literature work focused either on the modelling and optimization of individual processing sections, or on the assessments of the biogas production system. However, systematic optimization of the whole system considering multi indicators like economic performance and environmental impact which has a great significance to both future research and industrial applications, has not been reported.

The aim of this study is to establish a superstructure for a typical biogas production system considering nine kinds of common feedstock materials, three kinds of common heat supply technologies and four kinds of promising decarbonization technologies. Following this, the biogas production system is optimized with respect to the criteria of economic and environmental performance, and solved by employing non-dominated sorting genetic algorithm (NSGA II) [14]. Sensitivity analysis of methane and electricity price as well as plant scales, are performed and discussed.

2 Methodology

2.1 System description

The benchmark data of this work is based on the Nanjing University of Technology's biogas demonstration project, which have a biogas production of 500 m³ per day. The studied biogas production system is present in Figure 1, which consists of the following processing sections: Biomass collection and transportation, Pretreatment (chopping and briquetting), Co-digestion, Desulphurization, Dehumidification, Decarburization (PWS, ILs, PSA, MEA), Waste management (solid-liquid separation, drying, slurry concentration).

Figure 1. Biogas production and upgrading system

The mass flowrate of the feedstock (chicken feces mixes with crop straw and fresh water) is fixed at 13.6 ton/day. The total solid content (TS) in the feedstock is specified as 10%. The digestate slurry outlet from digester with higher temperature is used to pre-heat the biomass feedstock by a heat exchanger. The products from the whole system are 20 bar methane, solid fertilizer and liquid fertilizer. For PWS process, the CO_2 is emitted to the atmosphere directly; for other decarbonization processes, the resulting pure CO_2 is treated as product. The circulating water is used to prepare digestion feedstock. The detailed description of each sections are conducted in following sections, where the models of energy consumption, economic performance and biogas yield are included and explained, as part of the objective functions.

2.2 Models

2.2.1 Collection and transportation

The demonstration project is built in the livestock farm, so only the cost and energy consumption for collecting and transporting crop straw is considered. Wu et al. [12] developed an energy consumption model Eq. (1) for the process considering a circle collection area and a tortuosity factor to validate the straight line distance.

$$E_{c\&t} = FC_b \cdot FHV \cdot \tau \left[\frac{2}{3} Q^{1.5} (\pi\rho)^{-0.5} + (Q + m_{car}) \cdot s \right] / V_{CH4} \quad (1)$$

where $E_{c\&t}$ is the specific energy consumption for collection and transportation section, in MJ_{th}/Nm³ CH₄, where the subscript *th* indicates thermal energy; FC_b is the specific fuel consumption, in L fuel/(km ton); FHV is the lower heating value of the liquid fuel, in MJ_{th}/L; τ is the tortuosity factor, equal to 1.5; ρ is the distribution density of crop straw, in ton/km²; m_{car} is the mass of transport truck, in ton; s is the distance from livestock farm to crop straw collection site, in km; Q is the collection rate of crop straw, in ton/day; V_{CH4} is the volume flowrate of methane, in Nm³/day.

The cost of this section is only fuel cost from transportation by assuming no commercial value of chicken feces and crop straws. Then the cost is calculated by Eq. (2)

$$C_{c\&t} = \tau \cdot P_t \cdot \left[\frac{2}{3} Q^{1.5} (\pi\rho)^{-0.5} + (Q + m) \cdot s \right] \quad (2)$$

where $C_{c\&t}$ is the cost of collection and transportation section, in \$/day; P_t is the specific transportation cost, in \$/(ton km).

The mass flowrates of feedstock materials are calculated by Eqs. (3) – (4)

$$Q_{chickenfeces} = nQ_{i,straw} \quad (3)$$

$$Q_{chickenfeces} TS_{chickenfeces} + Q_{i,straw} TS_{i,straw} = 1.36 \quad (4)$$

where $Q_{chickenfeces}$ is the mass flowrate of chicken feces in feedstock, in ton/day; $Q_{i,straw}$ is the mass flowrate of *i* straw in feedstock, in ton/day; n is the mass ratio of chicken feces and crop straw; $TS_{chickenfeces}$ and $TS_{i,straw}$ are the solid content in chicken feces and *i* straw, $i = wheat, corn, rice$.

2.2.2 Pretreatment

Machines for chopping and briquetting are employed for the pretreatment of the crop straw to enhance its decomposition and hence the biogas yield.

Bitra et al. [15] presented the energy consumption model of the chopping process

$$E_{chop} = (54.02 - 0.05d - 10.45Q_{straw} - 0.16dQ_{straw} + 0.02d^2 + 1.12Q_{straw}^2) \cdot Q_{straw} \cdot 3.6 / (V_{CH_4} \cdot \eta_{HTE}) \quad (5)$$

Mani et al. [16] presented the energy consumption model of the briquetting process

$$E_{briq} = (4.76 + 1.48P_B - 0.19M + 0.032P_B M) \cdot Q_{straw} / 0.39 / V_{CH_4} \quad (6)$$

Total energy consumption was calculated by using Eq. (7)

$$E_{pre} = E_{chop} + E_{briq} \quad (7)$$

where E_{chop} , E_{briq} and E_{pre} are the specific energy consumption of chopping, briquetting, pretreatment processes, in $MJ_{th}/Nm^3 CH_4$, respectively. d is the particle size after chopping, in mm; Q_{straw} is the straw collection rate, in ton/day; η_{HTE} is conversion efficiency of thermal energy to electric energy, 0.39 [17]; P_B is the briquetting pressure, in MPa; M is moisture content of crop straw.

The equipment involved in this section are machines of chopping and briquetting, with fixed cost of 3000 \$ for each one. The variable cost is the power prices, calculated by Eq. (8).

$$EP_{pre} = EP_{pre} \cdot V_{CH_4} / 3.6 \cdot \eta_{HTE} \cdot P_{ele} \quad (8)$$

where EP_{pre} is the electricity cost per day, in \$/day; P_{ele} is the electricity price, in \$/kWh.

2.2.3 Co-Digestion

Co-digestion is the simultaneous digestion of a mixture of two or more substrates, with technological, ecological and economic advantages [18]. This project applied a mixture of chicken feces, crop straw (wheat straw, corn straw, rice straw) and fresh water as digestion feedstock. The biogas yield strongly depends on the types and composition of feedstock, the digestion temperature (T), and the residence time (t). The empirical equation of biogas yield is reported by Ou-yan et al. [19], as a function of T , t and substrate composition.

The energy consumption of an anaerobic digestion section mainly consists of four

parts: heat for heating the fresh feedstock ($E_{heating}$), heat loss of the digester due to convection heat loss (E_{loss}), power for mechanical agitation (E_{agi}) and the power for pumping the feedstock (E_{pump}). The models are presented in Eqs. (9) - (14). The power of the pump is necessary to estimate its investment cost and is calculated by Eq. (13) [20].

$$E_{heating} = (T - T_{amb}) \cdot C_{pm} \cdot Q_f / V_{CH_4} \quad (9)$$

$$E_{loss} = 24 \cdot 3.6 \cdot (T - T_{amb}) / 1000 \cdot \left(\frac{S_{side} + S_{top}}{\frac{\delta_D}{\lambda_D} + \frac{\delta_{ins}}{\lambda_{ins}} + \frac{1}{\alpha}} + \frac{S_{bot}}{\frac{\delta_D}{\lambda_D} + \frac{\delta_{ins}}{\lambda_{ins}}} \right) / V_{CH_4} \quad (10)$$

$$W_{agi} = 6t / 24.265 \quad (11)$$

$$E_{agi} = 86.4 W_{agi} / V_{CH_4} / \eta_{HTE} \quad (12)$$

$$W_{pump} = u(P_2 - P_1) / (\rho_f \eta_p \eta_m) / 1000 \quad (13)$$

$$E_{pump} = 24 \cdot 3.6 \cdot W_{pump} / V_{CH_4} \quad (14)$$

where $E_{heating}$, E_{loss} , E_{agi} , E_{pump} are the specific energy consumption by heating substrate, compensating heat loss, agitation and pumping, in $\text{MJ}_{th}/\text{Nm}^3 \text{CH}_4$, respectively; W_{agi} and W_{pump} are the power of agitator and pump, in kW, respectively. t is the digestion time, day; T and T_{amb} are the digestion and ambient temperature, in $^{\circ}\text{C}$, respectively. C_{pm} is the specific heat capacity of substrate in digester, assuming 4.2 $\text{kJ}/(\text{kg K})$, because it has similar property with water. Q_f is the mass flowrate of the feedstock, in ton/day; S_{top} , S_{bot} , S_{side} are the top, bottom and side areas of the digester, in m^2 , respectively, which can be easily calculated by assuming that the diameter equals to height; δ_{ins} and δ_D are the thickness of the insulation layer and the digester, in m, respectively. λ_{ins} and λ_D are the coefficient of thermal conductivity of the insulation layer and the digester, in $\text{W}/(\text{m K})$, respectively. α is the heat transfer coefficient, in $\text{W}/(\text{m}^2 \text{K})$; ρ_f is the feedstock density, in kg/m^3 ; P_1 and P_2 are the pressure before and after pumping, in bar, respectively. η_p and η_m are the efficiencies

of pump (0.5) and motor (0.9), respectively.

The equipment involved in the digestion section includes digester, pump, agitator and heat supply equipment. The equipment for heat supply includes three alternatives, i.e., solar collector, biogas boiler and biomass boiler. The price of digester and insulation is 100 \$/m³ [13], the price of agitator is estimated according to its power, around 700 \$/kW [21]. The prices of biogas boiler and biomass boiler are 4200 \$. The cost of solar collector is 150 \$/m² [22]. The investment cost (*IC*) of pump is estimated according to the bare module costs method reported by Biegler et al. [20], shown in Eqs. (15) - (16)

$$BC = C_0(S/S_0)^\alpha \quad (15)$$

$$IC = UF \cdot BC(MPF + MF - 1) \quad (16)$$

where *BC* is the base cost, and *IC* is the investment cost and *UF* is an update factor for current price, 4.91 [23]; *C₀* is the reference cost, in \$; *S₀* is the reference characteristic values of equipment like power and heat duty; *S* is the characteristic values of equipment; *MPF* and *MF* are material and pressure correction factor and module cost.

The area of solar collector is calculated according to Eq. (17)

$$A = (E_{heating} + E_{loss}) / (I \cdot \eta_j \cdot (1 - \eta_s)) \quad (17)$$

where *A* is the area of solar collector, in m²; *I* is intensity of solar radiation per day, in kJ/(m² day); η_j is the efficiency of solar collector, 0.55; η_s is the heat loss rate of pipeline and water storage tank, 0.1.

The power price is calculated by Eq. (18)

$$EP_{ferm} = E_{ferm} \cdot V_{CH_4} / 3.6 \cdot \eta_{HTE} \cdot P_{ele} \quad (18)$$

2.2.4 Desulfurization and Dehumidification

Biogas mainly consists of CO₂ and CH₄ and small amount of water vapor and trace amount of H₂S. Generally, the H₂S content in raw biogas is in the range of 200

to 2000 ppmv. The desulfurization method and setup as well as plant performance and economic factors are reported by Krischan et al. [24]. The water vapor in biogas ranges from 5% to 10%, depending on the temperature [25], assuming 7% in this study. Refrigeration dryer is employed for dehumidification. Its price and power is 4500 \$ and 3 kW, respectively.

2.2.5 Decarburization

The technology options for decarburization section include pressured water scrubbing (PSW), ionic liquid scrubbing (ILs), monoethanolamine scrubbing (MEA) and pressure swing adsorption (PSA). The modelling of these upgrading technologies is our previous work [10,26,27]. For the former three technologies, $L_{16}(4^3)$ orthogonal test is designed to obtain empirical models for key parameters, i.e. gas liquid ratios, the amount of circulating gas, diameter of columns and energy consumption.

The empirical formulas are used to determine the gas flowrate, circulating solvent flowrate, which are necessary to calculate the size and power of pump, compressor, blower, flash, and the investment of solvents. For PWS and ILs processes, the gas flowrate into the absorber is determined by Eq. (19); for MEA process, it's determined by Eq. (20). The circulating solvent flowrate in absorber is calculated by Eq. (21). For MEA process, the biogas flowrate in to the absorber is calculated by Eq. (22)

$$F_{feedgas} = \gamma \times V_{biogas} \quad (19)$$

$$F_{feedgas} = V_{biogas} \quad (20)$$

$$L = F_{feedgas} / (g/l_a) \quad (21)$$

$$F_{feedair} = L \times (g/l_s) \quad (22)$$

where $F_{feedgas}$ is the flowrate of gas into absorber, in Nm^3/day ; γ is the amount of circulating gas, in %; V_{biogas} is the flowrate of biogas, in Nm^3/day ; L is the flowrate of solvent, in m^3/day .

For PWS, ILs and MEA processes, their specific energy consumptions are

calculated according to the empirical models. For adiabatic PSA process, the energy consumption is estimated according to Eq.(23) [28].

$$E_{PSA} = \left(\frac{\gamma}{\gamma - 1} \right) RT_{feed} \left[\left(\frac{P_{high}}{P_{low}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \cdot \frac{F}{1000\eta} \cdot \frac{3.6}{V_{CH_4}} / \eta_{HTE} \quad (23)$$

where F is the flowrate of gas stream, in mol/s; P_{high} and P_{low} are the adsorption pressure and the desorption pressure, in bar, respectively. T_{feed} is the temperature of gas stream, in °C; $\gamma = C_p/C_v$, which assumes a value of 1.31; η is the mechanical efficiency, 0.8 in this study.

After decarbonization, a multistage pump is employed to compress the CH₄ to 20 bar to meet the natural gas grid requirement. The equipment involved in each processes are summarized in Table 1.

Table 1. Equipment involved in different processes

Process	Equipment
PWS	Absorber, Desorber
	Compressor × 2
	Blower
	Flash tank
	Pump
ILs	Absorber
	Compressor × 2, Vacuum pump
	Pump
	Flash tank × 2

MEA	Expander
	Absorber, Desorber
	Blower
	Pump $\times 2$
	Heat exchanger, Condenser, Reboiler
PSA	Adsorption column $\times 2$
	Compressor $\times 2$
Recompression	Multistage pump

The investment costs of pump, vacuum pump, compressor, blower, column, heat exchanger, reboiler and condenser (treated as heat exchangers), and flash are calculated by Eqs. (15), (16), (24) [20].

$$BC = C_0(L/L_0)^\alpha(D/D_0)^\beta \quad (24)$$

where L_0 , D_0 are the reference characteristic values of equipment like size, power and heat duty; L , D are the characteristic values of equipment.

The purchase cost of water, MEA solvent, [Bmim][Tf₂N] solvent and CMS-3K adsorbent is 0.46 \$/ton, 1500 \$/ton, 224900 \$/ton and 15000 \$/ton, respectively.

2.2.6 Waste management

In this study, the digestate is firstly sent to a screw-press for solid-liquid separation. Then solid fraction of digestate with 65% water content goes to a dryer machine to get solid bio-fertilizer. The liquid fraction goes to hybrid membrane technology for recovery of liquid fertilizer and industrial water [29]. The sand filter firstly traps the suspended material and bacterial. Then the permeate get through microfiltration membrane, ultrafiltration membrane and nanofiltration membrane successively to get the concentrated liquid fertilizer and circulating water. The operation pressure of MF membrane and NF is 2 bar and 4.8 bar, respectively. Hence two pumps are employed to meet the operation pressures. Assume that after concentration, permeation fluid accounts 80% of the total slurry flowrate. The energy

consumption for screw-press and dryer, $E_{sep\&dry}$, was established by Wu et al. [12] and shown in Eq.(25)

$$E_{sep\&dry} = (4.3 \times m_{slurry} + 130 \times m_{digestate})/V_{CH_4} \quad (25)$$

where m_{slurry} is the mass flowrate of the digestate slurry, in ton/day; $m_{digestate}$ is the mass flowrate of solid fraction of digestate, in ton/day.

The energy consumption for the two pumps and the waste management section is calculated by using Eq. (26) - (28).

$$W_{pump} = u(P_2 - P_1)/(\rho_f \eta_p \eta_m)/1000 \quad (26)$$

$$E_{pump} = 24 \cdot 3.6 \cdot W_{pump}/V_{CH_4} \quad (27)$$

$$E_{wm} = E_{sep\&dry} + E_{pump1} + E_{pump2} \quad (28)$$

where E_{wm} , E_{pump1} , E_{pump2} are the specific energy consumptions of waste management section, in MJ_{th}/Nm³ CH₄. EP_{wm} is the electricity price, in \$/day.

The electricity price is calculated by using Eq. (29)

$$EP_{wm} = E_{wm} \cdot V_{CH_4}/3.6 \cdot \eta_{HTE} \cdot P_{ele} \quad (29)$$

The cost of sand filter, microfiltration membrane, ultrafiltration membrane, nanofiltration membrane and biogas slurry pool is 1274 \$, 600 × 4 \$, 577 × 4 \$, 360 × 4 \$ and 6000 \$, respectively. The costs of pumps are calculated by using Eq. (15) and (16) from the previous section.

2.3 Optimization

2.3.1 Objective functions

In this study, the economic and environmental performance are evaluated using NPV method and Green degree method, respectively. The NPV of the biogas production system is calculated by Eqs. (30) – (31). The project is economically feasible if the NPV is positive [30].

$$NPV = \sum_{t=0}^N \frac{CF_t}{(1+r)^n} \quad (30)$$

$$CF_t = -CF_0 + \sum_{i=1}^t GM \quad (31)$$

where CF_0 is the initial investment, \$; GM is the gross margin per year, a constant value by assuming stable operation, \$; r is the discount rate, which assumes a value of 0.05.

Payback period (PB) and internal rate of return (IRR) are two important economic parameters for assessing economic feasibility of the process. They can be calculated according to Eqs. (32)-(33).

$$GM = CF_0 \left[\frac{r(1+r)^{PB}}{(1+r)^{PB} - 1} \right] \quad (32)$$

$$\sum_{t=0}^n \frac{CF_t}{(1+r)^t} = 0 \quad (33)$$

The initial investment (CF_0) is the total facility investment (TFI), which consists of two components i.e. base plant cost (BPC) and project contingency (PC); the gross margin (GM) is defined as the revenue of product minus the operation cost. The methodology was proposed by Hussain [31] and is shown in table 2.

Table 2. Economic and process factors for biogas project

Category	Value	Unit
Total Facility Investment (TFI)		
Fixed Cost (FC)	$FC = IC$	\$
Base plant cost (BPC)	$BPC = 1.12FC$	\$
Project contingency (PC)	$PC = 0.2BPC$	\$
Total facility investment (TFI)	$TFI = BPC + PC$	\$

Operating and Maintenance Cost (O&M)		
Water Cost (WC)	$WC = 0.46(Q_{feedstock} - Q_{straw} - Q_{feces} + 4/5 \cdot Q_{slurry})$	\$/year
Energy Cost (EC)	$EC_{ele} = E \cdot V_{CH_4} / 3.6 \cdot \eta_{HTE} P_{ele}$	\$/year
	$EC_{heat} = EC_{heat} \cdot V_{CH_4} / 3.6 \cdot P_{heat}$	
Labor cost (LC)	$LC = 0.1 \cdot OC$ [32]	\$/year
Local tax and insurance (LTI)	$LTI = 0.01 \cdot TFI$ [13]	\$/year
Maintenance Cost (MC)	$MC = 0.04 \cdot TFI$ [31]	\$/year
Operating and Maintenance Cost (O&M)	$O\&M = WC + EC_{ele} + EC_{heat} + LC + LTI + MC$	\$/year
Revenue of product(RP)	$RP = 0.5997V_{CH_4} \cdot 333$	\$/year
Gross margin (GM)	$GM = RP - O\&M$	\$/year

Green degree (*GD*) is a composite index proposed by Zhang et al. [33] for quantitatively assessing the environmental impact of a substance, stream or process based on nine environmental categories [33]. The Green degrees of substance, stream and process are calculated by Eqs. (34) – (39). A positive *GD* value indicates that the process is benign to environment.

$$GD_i^{su} = - \sum_j^9 (100\alpha_{i,j}\varphi_{i,j}^N) \quad (34)$$

$$\varphi_{i,j}^N = \varphi_{i,j} / \varphi_j^{max}, \varphi_j^{max} = \max(\varphi_{i,j}) \quad (35)$$

$$\sum_{j=1}^9 \alpha_{i,j} = 1 \quad (36)$$

$$i = 1, 2, 3 \dots; j = 1, 2, 3 \dots, 9$$

$$GD^{St} = F \times \sum_{k=1}^m GD_k^{su} x_k \quad (37)$$

$$\sum \Delta GD_j^{St} = \sum GD_k^{St,out} - \sum GD_i^{St,in} \quad (38)$$

$$\Delta GD^P = \sum GD_i^{Energy,in} + \sum \Delta GD_j^{St} \quad (39)$$

where GD_i^{su} is the green degree of substance *i*, gd/kg; GD^{St} is the green degree of the stream, gd/day; $GD_i^{St,in}$ and $GD_k^{St,out}$ is the green degree of input and output material stream, gd/day; ΔGD_j^{St} is the green degree production of the stream, gd/day; GD^P is

the green degree of the process, gd/day; F is the mass flowrate, kg/day; x_k is the mass fraction of substance k ; $GD_i^{Energy,in}$ is the green degree of the input energy, gd/day.

Based on models established above, seven important variables were chosen for our optimization problem: digestion temperature, residence time, absorption pressure, lean liquid loading, types and compositions of biomass, decarbonization technologies and heating modes of digester. They are summarized in Table 3.

The presented energy and economic model are coupled with the mass balance models for each technology in formulation of the optimization problem. Gas densities of biogas, CO_2 and CH_4 are 1.276 kg/m^3 , 0.717 kg/m^3 and 1.96 kg/m^3 , respectively, which are necessary for mass balance.

Table 3. Variables of the optimization problem and their boundaries

Property		Variables	Variables specification	Boundary	Unit
Global		T	Digestion temperature	[35,55]	°C
variables	Continuous	t	Residence time	[18.7,29.3]	day
Local	variables	P_{abs}	Absorption pressure	[7,10]	bar
variables		ε	Lean liquid loading	[0.13,0.28]	-
		x	Types and composition of biomass	[1,9]	-
Global	Integer				
variables	variables	y	Biogas decarbonization techniques	[1,4]	-
		z	Heating mode of digester	[1,3]	-

Note that the local variables are activated only when relevant technologies are selected. The absorption pressure will be activated when ILs and PWS technologies are selected. The lean liquid loading will be activated when MEA technology is selected.

2.3.2 Multi-objective optimization formulation

With all these models, variables and objective functions, a mixed-integer nonlinear programming (MINLP) problem is formulated and solved with a real-coded

non-dominated sorting genetic algorithms- II (NSGA- II) to maximize the NPV and Green degree simultaneously. The MINLP model is coded in MATLAB. All the computational studies are performed on a workstation with an intel Xeon® processor E5-2670 v3 2.30 GHz-CPU, and 64-GB (8×8GB) RAM. The population size is set as 1000, and the number of generation is set as 6000. The crossover probability of crossover (P_c) and mutation (P_m) are 0.9 and 0.1, respectively.

3 Results and Discussion

3.1 Optimization results

The program is implemented 10 runs, from which the consistent Pareto-optimal solution set is obtained. The Pareto solutions are generated with respect to two objectives, shown in Figure 2. Note that the true Pareto front is difficult to obtain, hence in industrial a reference solution set is used to represent it. The Pareto curve shows the optimal trade-off designs of the biogas production system. Each Pareto point on the three curves represents the optimal design of the biogas production system with unique tradeoff between the NPV and Green degree. As shown in Figure 2, the environmental impact is positive for all the Pareto solutions, in the range of 1.23×10^5 gd/year to 1.75×10^5 gd/year. The NPV is positive for all the Pareto solutions, from 0.30×10^5 \$ to 1.40×10^5 \$. So the solutions are feasible in both environmental and economic considerations. Curve A presents highest average Green degree, but lowest average NPV. Curve C presents highest average NPV, but lowest average Green degree.

The technology combinations of these three curves are shown in Table 4. According to the simulation results listed in Table 4, 3:1 (wt%) chicken feces and rice straw and 3:1 (wt%) chicken feces and corn straw are demonstrated to be the optimal two feedstock among the feedstock candidates in this study. PSA is demonstrated to

be the optimal decarbonization option. The ILs and PWS technologies have relative low energy consumption but high fixed cost. Because they are physical absorption with relative low absorption capacity, hence they have large amount of circulating solvent, resulting in large equipment sizes and high fixed cost. The advantages of lower energy consumption can not compensate their disadvantages of higher fixed cost, so they died in the evolution. The MEA process is based on chemical absorption with high absorption capacity, so it has small equipment size and fixed cost. But it has much higher energy consumption due to higher reboiler duty. And the extra electricity cost associated with energy consumption can compensate the advantages of fixed cost. So the MEA process died in the evolution. The PSA technology has relative low fixed cost, low energy consumption and it doesn't emit CO₂ to the environment hence it's optimal in both economical and environmental considerations. By comparing curves A and B with C, solar energy has advantage regarding environmental feasibility while biomass boiler has advantage regarding to economic feasibility. Because the solar collector is expensive while the biomass boiler is cheap but it releases flue gases like CO₂, SO₂ and NO_x. Biogas to supply heat demand doesn't appear in the optimized profile hence it's demonstrated to be an un-ideal choice.

Table 4. The optimized technology combinations

Pareto curve	Feedstock	Heat supply	Decarbonization technology
A	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
B	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA

C   3:1 (wt%) chicken   Biomass boiler   PSA
feces and corn straw

Figure 2. Pareto optimal curve

By visual inspection, the Pareto fronts in different technology combinations have similar trend. The NPV are increasing in the direction from Pareto point A1 to C3 at the expense of decreasing the Green degree value, which shows the tradeoff relations between NPV and Green degree. A1 has the highest Green degree of 174830 gd/year due to its lowest energy consumption and the use of solar collector. But it has the lowest NPV 30191 \$ due to its lowest biogas yield resulting from the lowest digestion temperature and shortest residence time. C3 has the highest NPV 139850 \$ and the lowest Green degree 123460 gd/year.

The goal of the optimization is to maximize these two objectives simultaneously, but along the Pareto front no objective can be improved without the expense of other objectives. The region above the Pareto front is the infeasible region.

Table. 5 The process configurations and performance of the selected Pareto points

No.	T (°C)	t (day)	NPV (\$)	GD (gd/year)	V_{biogas} (Nm ³ /day)	Energy consumption (MJ _{th} /day)	Operation cost (\$/year)	Total fixed cost (\$)	Product revenue (\$)	Payback Period (year)	Internal Rate Return(%)
A1	40.2	18.7	30191	174830	423.0	5240.0	31849	212620	48170	16.8	4.5%
A2	46.8	19.7	80266	168900	478.4	5475.7	33511	231720	54481	13.6	6.5%
A3	46.9	25.4	115140	155000	533.6	5974.1	36071	252300	60769	12.4	7.5%
B1	35.0	20.8	115390	154330	495.5	5606.0	33628	223860	56430	11.8	8.0%
B2	35.3	22.5	125750	150180	512.3	5755.1	34406	230300	58338	11.5	8.3%
B3	35.9	24.3	129450	146250	524.4	5893.2	35128	236370	59716	11.5	8.3%
C1	45.6	23.1	129450	132760	515.2	5785.1	34624	228330	58672	11.3	8.5%
C2	46.4	23.9	135310	129440	523.9	5860.0	35016	231340	59661	11.2	8.6%
C3	48.0	25.4	139850	123460	534.6	5977.8	35626	235870	60880	11.1	8.7%

The operation condition and system performance for selected Pareto points are shown in Table 5. The digestion temperature is distributed between 35°C and 48°C and the residence time is distributed between 18.7 day and 25.4 day. Higher digestion temperature can consume a lot of energy and decrease the biogas yield simultaneously. Longer digestion time can result in large digestion volume and large agitation energy consumption hence higher fixed cost and energy consumption.

Pareto point B1 is selected and analyzed to reveal the sections cost distribution, the cost distribution of equipment in each section, the energy distribution and the green degree distribution of the system. Figure 3 presents the equipment purchase cost distribution of Pareto point B1. The most expensive equipment is the anaerobic digester, followed by compressor1 and compressor2 in the PSA process, and the desulfurization setup. The fixed cost distribution between processing sections is shown in Figure 4. The most expensive processing section is decarbonization, followed by digestion and waste management, respectively. Figure 5 presents the energy consumption distribution among seven processing sections. As shown in Figure 5, 28.40% of the total energy consumption is attributed to the digestion section, which includes the energy consumption of agitation and pumping. Within the digestion section, the agitation contributes 72.70% of the energy consumption of the digestion section. 27.92% of the total energy consumption is attributed to the decarbonization section, which includes the energy consumption of compressor1, compressor2. 27.79% of the energy consumption is attributed to waste management section, which includes the energy consumption of pump2, pump3 and screw press and dryer. Within the waste management section, the pump2 and pump3 contribute 22.82% and 64.55% of the energy consumption,

respectively, and the screw press and dryer contributes 12.62%. It's hence concluded that most of the energy consumption comes from the pumps; membranes with better performance and at lower working pressure needs special attention in the research and development. Figure 6 presents the *GD* distribution between processing sections. All the processing sections except decarbonization and waste management have negative Green degree. The decarbonization section has the lowest Green degree, which indicates the worst environmental performance. The Green degree of the decarbonization section is attributed to its energy consumption, and the decarbonization has very high energy consumption share as shown in Figure 5. Note that the Green degree of energy consumption is calculated based on the environmental impact associated with the energy production. For the digestion section, on one hand, it consumes a lot of energy. On the other hand, it converts biomass waste with negative *GD* value to crude biogas product with *GD* of 0 and biogas digestate with less environmental impact, which has positive Green degree. Compromise of the two effects mentioned above resulted in the positive Green degree, which indicates an environmental friendly process. This processing step is the biggest contributor in terms of numerical value, hence it's key to have an environmental friendly process. For the waste management section, although it consumes a lot of energy, it converts biogas digestate into fertilizer product with *GD* of 0. Compromise of these two effects resulted in the positive Green degree, which indicates an environmental friendly process. For the processing sections of collection and transportation, pretreatment, desulfurization and dehumidification, their Green degree are attributed to their energy consumption.

Figure 3. The equipment purchase cost distribution.

Figure 4. The processing sections purchase cost distribution.

Figure 5. The energy distribution between processing sections.

Figure 6. The green degree distribution between processing sections.

3.2 Sensitivity analysis

Since the prices of electricity and methane fluctuate frequently and different plant scales are required in industrial application, hence sensitivity analysis is conducted for them one by one, in order to study their effects on the optimized profiles and to study the robustness of the

Pareto solutions. The optimized profile at different prices of electricity and methane is shown in Table 6.

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Table 6. The optimized technology combinations at different conditions

Electricity price	Feedstock	Heat supply	Decarbonization technology
0.07 \$/kWh	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Biomass boiler	PSA
	3:1 (wt%) chicken feces and corn straw	Biomass boiler	PSA
0.08 \$/kWh	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and corn straw	Biomass boiler	PSA
0.09 \$/kWh	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Biomass boiler	PSA
Methane price	Feedstock	Heat supply	Decarbonization technology
0.55 \$/Nm ³	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Biomass boiler	PSA
0.57 \$/Nm ³	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and corn straw	Biomass boiler	PSA
0.59 \$/Nm ³	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Biomass boiler	PSA
Plant scale	Feedstock	Heat supply	Decarbonization technology
500 Nm ³ /day	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and corn straw	Biomass boiler	PSA
1000 Nm ³ /day	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and corn straw	Biomass boiler	PSA
2000 Nm ³ /day	3:1 (wt%) chicken feces and corn straw	Solar energy	PSA
	3:1 (wt%) chicken feces and rice straw	Solar energy	PSA
	3:1 (wt%) chicken feces and corn straw	Biomass boiler	PSA

The electricity price can affect the two objective functions by affecting the energy consumption of the system hence to affect its methane yield and operating cost. The methane price can affect the objective functions by affecting the methane yield. As a result, new Pareto solutions including technology combinations and operation conditions are obtained at different electricity price and methane price, as shown in table 6. It's interesting that some technology combinations are included in all the optimized profiles, i.e. 3:1 chicken feces and corn straw, solar energy, PSA and 3:1 chicken feces and rice straw, solar energy, PSA, which indicates robust technology combinations. It is also found that the plant scale has no effect on the optimized technology combinations. Consequently, these technology combinations can be safely extended to other scales.

4 Conclusions

Pareto fronts and solutions were obtained and analyzed for the biogas production system. The results indicate an environmental friendly and economically feasible process and can provide strategy for design and operation of the biogas production system. It's found that the most expensive processing section is decarbonization; the most expensive equipment is anaerobic digester; the most power-consuming processing section is digestion, followed by decarbonization and waste management. The positive green degree value on the process is attributed to section of digestion and waste management. 3:1 chicken feces and corn straw, solar energy, PSA and 3:1 chicken feces and rice straw, solar energy, PSA are turned out to be two robust technology combinations under different prices of methane and electricity by sensitivity analysis.

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