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ScienceDirect

Energy Procedia 158 (2019) 700–705

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Product-Energy Cascade Analysis (PENCA) for integrated product and energy system optimization

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Abstract

This paper presents an optimisation method called the Product-Energy Nexus Cascade Analysis (PENCA), developed based on the principal of Pinch Analysis. Product and energy are both valuable resources that are majorly used in industrial processes. Both product and energy are interdependent where increasing product demand will increase the energy demand and vice versa. In this paper, PENCA is introduced to simultaneously optimise both product and energy system that is interdependent. The methodology applies Cascade Analysis to individually optimise both system. As both systems are interdependent, altering one of the system will result in a change to the other system. An iterative method is then introduced to converge the analysis to obtain the optimal result for both systems. A case study is conducted to prove PENCA methodology, in which biogas is used as cooking gas and used to generate electricity and for a residential area of 500 households. A typical household with a daily electricity consumption of 9 kWh and cooking gas 31.06 kWh is estimated for this study. The power plant will also produce electricity to operate the palm oil mill. The production of biogas requires electricity as well due to the presence of electrical machineries in anaerobic digestion and purification process such as pump and compressor. An overall of 4 iterations were conducted and the final capacity of the anaerobic digester is revealed as 474.180 m^3 and the biogas power plant capacity is 1522.769 kWh, the biogas storage capacity is extracted and revealed as 1065.003 m^3, while the energy storage capacity is 750.00 kWh.

Keywords: Nexus; biogas optimisation; pinch analysis

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Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.
10.1016/j.egypro.2019.01.189

1. Introduction

Malaysia depends heavily on fossil fuels such as natural gas and coal as its key sources for electricity generation but decades of excessive exploitation of these natural resources has caused not only contamination, but contributes towards climate change and global warming as well. Realizing that the fast diminishing resources are not replenishing fast enough to cater from such unrelenting consumption, the Malaysian Government initiated a push for renewable energy (RE) since 2001 as a cleaner alternative solution. One of the potential source of energy in Malaysia is biogas which is extracted from the byproduct or the effluent called Palm Oil Mill Effluent (POME) through anaerobic treatment. Since Malaysia is the largest exporter of palm oil, hence the production of POME is also abundant hence has a higher potential as a renewable fuel source of energy.

However, POME need to be treated before it can be used as a fuel source of energy. Where as, to operate the palm mill and also the upgrading processes of biogas consume electricity. This relationship can be explained further as a nexus structure where both resources need each other for their operation process. The demand of electricity and biogas can be optimized by a few tools such as cascade analysis using Pinch Analysis (PA) method. PA is a technique to predict optimal performance of a process prior to actual design hence best used at preliminary stage to assist in decision-making process. Due to this advantage, PA has evolved over the decade from a tool for energy conservation [1] into an analytical tool for process integration and optimisation. PA can be categorised under two models. The first model as introduced by [1], known as supply-demand model, presents a Pinch method with quality versus quantity without considering time factor. The second model presents a model that relate quantity within a period of time (quality) [2]. In addition to these fields of work, [3] has demonstrated a numerical method based on PA called the Electricity System Cascading Analysis (ESCA). This methodology is very useful for designing and optimising power generators (biomass, biogas, solar and more) and energy storage for energy system.

Previous studies on PA including ESCA only considers a single source of resource during the analysis. In a case of integrating and designing system consisting of multiple resources, there is the possibility that both resource may be inter-correlated affecting the design of the system. A study by [4] presented a new methodology using two resources being simultaneously optimized called Water-Energy Nexus Cascade Analysis (WENCA). This study will present the similar methodology being applied with some different resources which is biogas as by-product from palm mill with energy as the dependent resource. These interactions were not explored in previous studies, as considering the relation between by-product of a process and energy can improve the design parameter resulting in a more accurate result. Synergies between byproduct and energy systems offer opportunities to compound benefits of an optimized process with optimum design capacity.

Nomenclature

POME	Palm Mill Oil Effluent
E	Energy
B	Biogas

2. Methodology and case study

The objective of this study is to optimize capacities of anaerobic digester (AD), biogas storage, biogas power plant and energy storage for a known total demand profile of residential and palm oil mill with the consideration of energy conversion efficiency for different biogas qualities.

Step 1: For the period of analysis, a period of 24 hours is selected. The system configuration comprises of anaerobic digester that will generate biogas from POME, which will then be used as the feedstock for biogas power plant. Biogas as the main product from the anaerobic digestion is produced to supply for the biogas power plant and residential cooking gas demand. However, to produce biogas the process required turbomachinery electric appliances such as pump and compressor. Therefore, when the electricity demand increase, it will cause biogas demand to increase. Similarly, when the biogas demand increase will cause electricity demand to increase. On the other hand, a typical household with a daily load profile of 9kWh of electricity and 31.06 kWh of cooking gas has been adopted for this case. The total demand is to supply electricity and biogas for 500 unit of houses on a community basis. On a common community basis, 500 residents have been measured to supply the generated resources. Charging and discharging efficiency is assumed as 100% without seeing the depth of discharge for capacity.

Step 2: The user is needed to roughly estimate the production of biogas electricity demand, kWh. In this designstudy, the initial amount estimated is 10kWh.

Step 3: Cascade analysis for electricity will then be conducted. Total amount of electricity to be generated based on palm oil mill and residential demands are arranged hourly in column while amount of electricity supply is calculated by using equation 1.

$$S_E = \frac{\sum D_{ET}}{24} \tag{1}$$

Then, net electricity demand is obtained by using equation 2. If the amount is positive (surplus), should be located in storing column. If it's negative amount (deficit) should be located in discharging column. Note that electricity surpluses show excess electricity (to be stored into the power storage), whereas electricity deficits show insufficient of electricity to meet the demand, thus extra source of electricity is necessary from the energy storage.

$$N_E = S_E - D_{ET} \tag{2}$$

Then, cumulative amount for first hour is calculated by equation 3. For 2nd hour till 24th hour is calculated by using equation 4.

$$C_{E,\ t=1.00} = 0 + D_E \tag{3}$$

$$C_{E,\ t=n} = C_{E,\ t=n\text{-}1.00} + D_{E,\ t=n} \tag{4}$$

In cumulative electricity (C_E) column, it should be examined the highest negative number and be located on the most top of new cumulative column (C_{EN}) as a positive number. If there is no negative amount, zero is then stated. The amount of electricity supply obtained (S_E) is then used to determine the biogas demand by using conversion shown in equation 5. Based on material balance, to produce 1kWh of electricity needed an average of $0.2489m^3$ of biogas by using anaerobic digestion method [5].

$$D_{BE} = (0.2489)S_E \tag{5}$$

$$D_{EA} = (4.0169)S_B \tag{6}$$

Once D_{BE} amount is obtained, biogas cascade analysis is conducted. Once biogas cascade analysis has been done, biogas supply amount obtained is converted using equation 6 to obtain a new production of biogas electricity demand. Based on material balance, to produce $1m^3$ of biogas needed an average 4.0169kWh for anaerobic digester and purification process. The cascade table for both electricity and biogas is repeated again (iteration, i) to proceed with percentage change at step 4.

Step 4: Percentage change is calculated using equation 7.

$$P = \frac{|S_{E,i=2} - S_{E,i=1}|}{S_{E,i=2}}\text{; } i\text{=iteration} \tag{7}$$

If the percentage of change is higher than 0.01%, the iteration should continue until it reaches below 0.01%. The percentage of 0.01% set as a tolerance to ensure the accuracy of the results

3. Results and discussion

Figure 1 shows the configuration of the biogas plant and the biogas power plant system. In this system configuration, POME undergoes anaerobic digestion and purification process to produce biogas. Biogas is used as cooking gas and used to generate electricity and for a residential area of 500 households. A typical household with a daily electricity consumption of 9 kWh and cooking gas 31.06kWh is estimated for this study. The power plant will also produce electricity to operate the palm oil mill. The production of biogas requires electricity as well due to the presence of electrical machineries in anaerobic digestion and purification process such as pump and compressors. Biogas and electricity are interdependent in anaerobic digestion and purification process where the increasing demand of biogas will then increase the electricity demand and increasing the electricity demand will increase the biogas demand.

In this study, the analysis begins by performing the cascade analysis for the electricity. The initial approximation of the production of biogas electricity demand is 10 kWh (Step 1), while the resulting biogas power plant capacity is 1447.500 kWh (Step 2). In Step 3, the corresponding biogas required to produce electricity is calculated as 360.352 kWh. The biogas demand by the electricity is added into the residential energy demand and biogas cascade analysis is conducted. It was identified that the anaerobic digester capacity is 455.441 m^3.

A number of 3 iterations were conducted using cascade analysis and the final capacity of the anaerobic digester is revealed as 474.180 m^3 and the biogas power plant capacity is 1522.769 kWh, the biogas storage capacity is extracted and revealed as 1065.003 m^3, while the energy storage capacity is 750.00 kWh (Step 5). The summary of the iteration and corresponding capacity for each iteration is as shown in Table 1. Table 2 and Table 3 show the final cascade analysis for the biogas and the electricity system. From Table 3, there are 4 iterations done for this case study. This is due to the percentage of changes calculated using equation 7 is higher than 0.01 for the first 2 iterations. The percentage for biogas and electricity capacity is calculated and it is less than 0.01% on the 4th iteration. Thus, it is considered to stop the iteration at the 3rd time and the result is accepted as a result of PENCA. The superscript, E represent the Biogas power plant and superscript, B represent the Biogas plant.

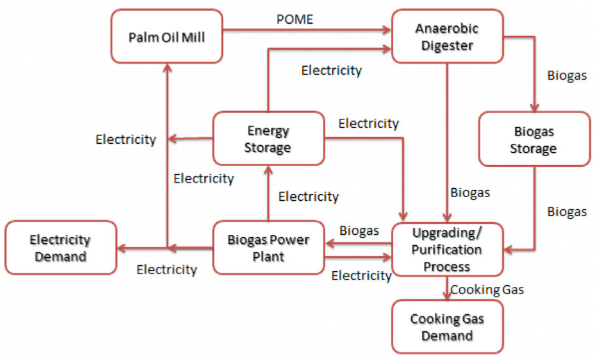

Figure 1: Biogas Electricity system configuration

Table 1. Summary of design capacities

Number of Iteration	Biogas power plant capacity (kWh)	Battery capacity (kWh)	AD capacity (m^3)	Biogas storage capacity (m^3)
1	1,447.500	750.000	455.441	1,065.003
2	1,519.406	750.000	473.342	1,065.003
3	1,522.625	750.000	474.144	1,065.003

Table 1. Electricity cascade analysis

t, h	Electric Demand, kWh			D_{ET}, kWh	S_E, kWh	N_E, kWh	Energy Storage, kWh		C_E, kWh	C_{EN}, kWh
	D_{ER}	D_{EM}	D_{EA}				S_{TE}	D_E		
									0	138
1	1523	125	1250	85	1460	63	63	0	63	200
2	1523	100	1250	85	1435	88	88	0	150	288
3	1523	50	1250	85	1385	138	138	0	288	425
4	1523	100	1250	85	1435	88	88	0	375	513
5	1523	100	1250	85	1435	88	88	0	463	600
6	1523	50	1250	85	1385	138	138	0	600	738
7	1523	175	1250	85	1510	13	13	0	613	750
8	1523	375	1250	85	1710	-188	0	-188	425	563
9	1523	500	1250	85	1835	-313	0	-313	113	250
10	1523	200	1250	85	1535	-13	0	-13	100	238
11	1523	300	1250	85	1635	-113	0	-113	-13	125
12	1523	300	1250	85	1635	-113	0	-113	-125	13
13	1523	200	1250	85	1535	-12	0	-12	-137	0
14	1523	90	1250	85	1425	98	98	0	-40	98
15	1523	100	1250	85	1435	88	88	0	48	185
16	1523	90	1250	85	1425	98	98	0	145	283
17	1523	90	1250	85	1425	98	98	0	243	380
18	1523	90	1250	85	1425	98	98	0	340	478
19	1523	165	1250	85	1500	23	23	0	363	500
20	1523	100	1250	85	1435	88	88	0	450	588
21	1523	150	1250	85	1485	38	38	0	488	625
22	1523	450	1250	85	1785	-263	0	263	225	363
23	1523	350	1250	85	1685	-163	0	163	63	200
24	1523	250	1250	85	1585	-62	0	62	0	138

Table 2. Biogas cascade analysis

t, h	Biogas Demand, m^3		D_{BT}, m^3	S_B, m^3	N_B, m^3	Biogas Storage, m^3		C_B, m^3	C_{BN}, m^3
	D_{BCG}	D_{EA}				S_{TE}	D_E		
								0	571
1	379	0	379	474	95	95	0	95	666
2	379	0	379	474	95	95	0	190	761
3	379	0	379	474	95	95	0	285	856
4	379	0	379	474	95	95	0	380	951
5	379	0	379	474	95	95	0	475	1046
6	379	228	607	474	-133	0	-133	342	913
7	379	228	607	474	-133	0	-133	209	780
8	379	0	379	474	95	95	0	304	875
9	379	0	379	474	95	95	0	399	970
10	379	0	379	474	95	95	0	494	1065
11	379	456	836	474	-361	0	-361	133	704
12	379	456	836	474	-361	0	-361	-228	342
13	379	0	379	474	95	95	0	-133	437
14	379	0	379	474	95	95	0	-38	533
15	379	0	379	474	95	95	0	57	628
16	379	0	379	474	95	95	0	152	723
17	379	456	836	474	-361	0	-361	-209	361
18	379	456	836	474	-361	0	-361	-571	0
19	379	0	379	474	95	95	0	-475	95
20	379	0	379	474	95	95	0	-380	190
21	379	0	379	474	95	95	0	-285	285
22	379	0	379	474	95	95	0	-190	380
23	379	0	379	474	95	98	0	-95	475
24	379	0	379	474	95	95	0	0	571

Table 3 shows the result of optimized capacity when the energy and biogas integration is considered using PENCA and also without biogas and energy integration. It could be identified that by considering biogas and energy integration, the anaerobic digester capacity, biogas power plant capacity are higher since the integration in PENCA involve biogas and electricity. Whereas the biogas storage capacity and energy storage capacity are remaining the same for both since both have similar net biogas demand, and net energy demand. As compared, in order to go for biogas and energy integration, PENCA allow the users to determine the most suitable integration within the existing units, in order to identify the minimum potential modifications in the existing energy and biogas production and distribution system. The fundamental principle behind the approach is the ability to match individual demand with a suitable supply. Hence, through the case study presented, PENCA is found to be an integrated technique that is best for resource optimization with simple methodology.

Table 3 Design capacity comparison with integration and without integration of electricity and biogas

Method	AD capacity (m^3)	Biogas storage capacity (m^3)	Biogas power plant capacity (kWh)	Battery capacity (kWh)
Integrated biogas and electricity system	474.180	1,065.003	1,522.769	750.000
Without integration (biogas system)	452.952	1,065.003	-	-
Without integration (electricity system)	-	-	1,437.500	750.000

Through the case study, it can be concluded that PENCA is a capable tool to determine the biogas power plant capacity, power storage capacity, anaerobic digester capacity and biogas storage capacity. This has successfully covers the biogas-energy nexus through numerical method which is derived from pinch analysis. This is mainly useful for design engineers to improve an integrated system between biogas and energy to optimize resources usage through biogas-energy nexus theory.

Acknowledgements

This research paper is financially supported by the Universiti Teknologi Malaysia (UTM) under the Grant vot no. Q.J130000.2446.03G61 and Grant vot no. Q.J130000.2546.12H89.

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