PAPER • OPEN ACCESS

Modelling and optimization of biomass-based cogeneration plant

To cite this article: N.A.A Abdul Razak and Abdulhalim Abdulrazik 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **257** 012027

View the article online for updates and enhancements.

IOP ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

This content was downloaded from IP address 103.53.34.15 on 17/07/2019 at 09:28

IOP Conf. Series: Earth and Environmental Science **257** (2019) 012027 doi:10.1088/1755-1315/257/1/012027

Modelling and optimization of biomass-based cogeneration plant

Abdul Razak N.A.A[1] and Abdulhalim Abdulrazik[1*]

1 Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang, Kuantan, Pahang, Malaysia.
*E-mail: abdhalim@ump.edu.my

Abstract. High energy demand and energy availability lead to the increasing of unpleasant energy situation. It is exacerbated if fossil fuels are the only energy source as it contributes to climate change and global warming. Thus, governments are focusing on the usage of natural resources as fossil fuel substitution. This study focused on the modelling and optimization of biomass-based cogeneration plant. The objective was to model, simulate and optimize the cogeneration plant which used torrefied EFB pellet as fuel in Aspen Plus simulator. Firstly, suitable biomass resources in Malaysia was identified. Next, a typical process flow diagram of cogeneration from the published literature was referred. Then, parametric and structural optimization were conducted. From the simulation, 1.764 MW of power was generated and it was observed that pellet flow rate, water flow rate, air flow rate and boiler temperature influenced the power generated. Five options with different structural designs were formulated in GAMS. It was found that the plant should focused on producing power and medium pressure steam to optimize the profit. The findings concluded that biomass-based cogeneration plant was technically feasible to be deployed. However, further refinements in the optimization aspect should be developed to obtain a more accurate optimal results.

1. Introduction

Nowadays, developing countries such as Malaysia faces energy crisis including power due to rapid growth of energy demand compared to developed countries [1]. Meanwhile, fossil fuels such as coal and natural gas which are the main energy sources in Malaysia, cannot be preserved anymore due to the lack of reserves and environmental impacts such as climate change and global warming [2]. Besides, the abundance of wastages production is eventually occurring [3]. Thus, exploration of new technologies and alternative energy sources must be increased in order to support the drastic population growth and energy demand. The Malaysian government had initiated an alternative solution by announcing a Small Renewable Energy Power (SREP) program to encourage private sectors to invest in small power generation projects utilizing renewable energy sources such as biomass and solar energy [4]. This program has raised the power industry's interest towards cogeneration plant. Cogeneration has become an option as it produces industrial energy need with more economically and efficiently compared to the conventional plant due to its effective use of wasted thermal energy [5]. Furthermore, Malaysia being one of the world's primary palm oil producers begins to encourage the use of renewable energy especially in palm oil due to its availability, continuity and capacity for renewable energy solution [6]. However, there are only few references available regarding biomass-based cogeneration plant especially in the modelling and simulation perspective. This research revised a more in depth of modelling and optimization of cogeneration plant using biomass in Malaysia. Major issue for this potential is the modelling and process analysis as it is

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

better to model, simulate and improve the system through optimization before constructing it. To simulate the process, Aspen Plus was chosen for this study as it is a powerful simulation tool for chemical engineering in various fields including oil and gas production, refining and power generation [7]. Meanwhile, General Algebraic Modeling System (GAMS) was used as an optimization tool to solve mixed integer optimization problem [8]. Hence, Aspen Plus modelling and usage of GAMS for optimization tools of cogeneration plant by using biomass would be a contribution for this work. The objectives were to model and simulate the cogeneration plant which uses biomass as fuel in Aspen Plus and to improve the biomass-based cogeneration plant by optimization. The scopes of study for this research covered the modelling, simulation and optimization of biomass-based cogeneration plant where treated biomass in the form of torrefied empty fruit bunches (EFB) pellet was used as a fuel and the targeted power produced was 1.3 MW.

2. Materials and methods

Figure 1 shows the sequence in order to achieve the objective. Explanation of each of the block will be explained in the following sections.

Identify suitable biomass resources found in Malaysia
↓
Obtain typical process flow diagram of cogeneration from the published literature
↓
Develop Aspen Plus model of cogeneration plant using biomass
↓
Simulate, validate and analyse the result
↓
Improve further the cogeneration process through optimization
↓
Conduct parametric optimization from simulation model and analyse the results
↓
Conduct structural optimization by using GAMS and analyse the results

Figure 1. Process flow diagram of the study

2.1. Identify suitable biomass resources found in Malaysia

Findings and observations regarding biomass in Malaysia were carried out where torrefied empty fruit bunches (EFB) pellet was chosen for this study.

2.2. Obtain typical process flow diagram of cogeneration from the published literature

A research on process flow diagram (PFD) of cogeneration plant from published literature was carried out where it was used as a reference for modelling and result validation purposes. Figure 2 shows the chosen PFD from Wu et.al. (2017) as a base case study where oil palm waste as fuel.

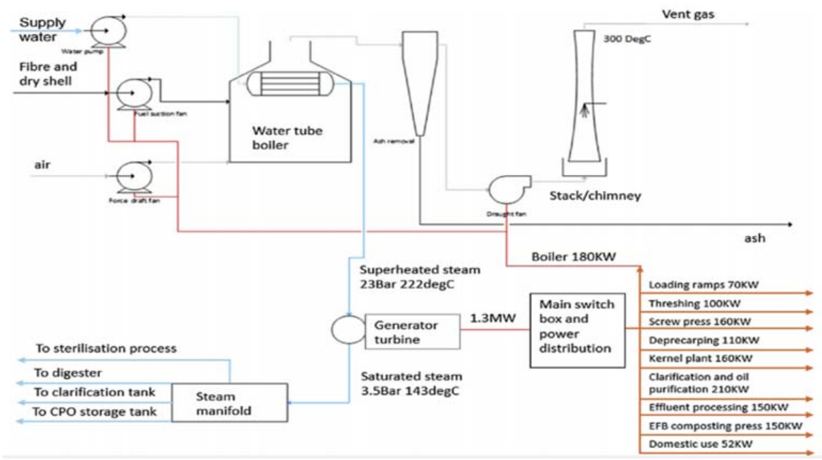

Figure 2. Process flow diagram of a biomass-based cogeneration plant [9]

2.3. Develop Aspen Plus model of cogeneration plant using biomass

Figure 3 shows the model of biomass-based cogeneration plant developed by using Aspen Plus where the PFD and operating conditions were referred to the published journal by Qibai Wu et.al.

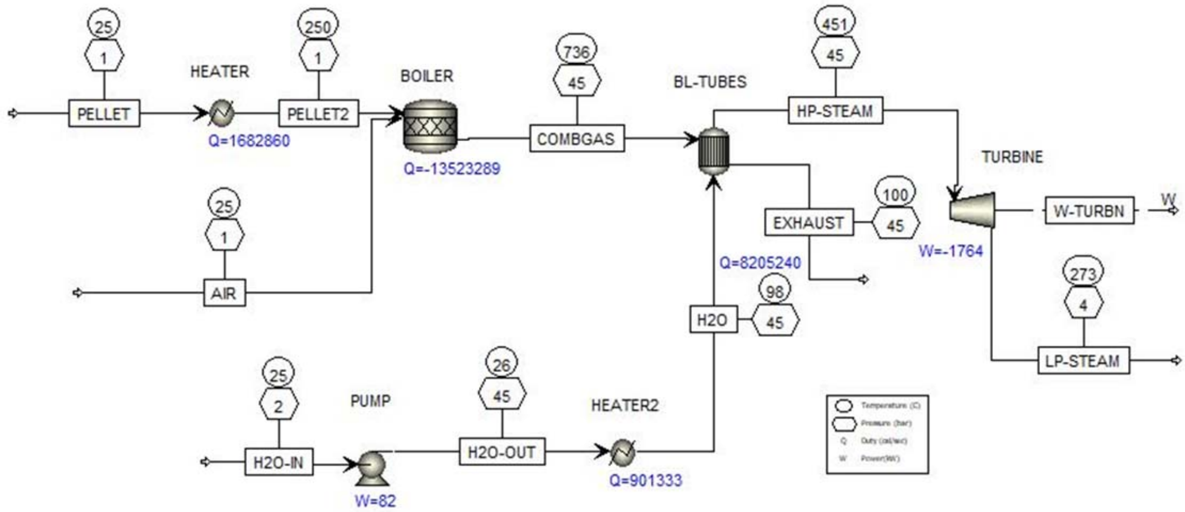

Figure 3. Flowsheet of biomass-based cogeneration plant in Aspen Plus

The components involved were carbon graphite, hydrogen, nitrogen, oxygen, sulphur, water, carbon dioxide, nitric oxide and nitrogen dioxide. The operating conditions for the inlet streams were shown in Table 1.

Table 1. Table of operating conditions for the inlet streams [9]

Stream	Operating conditions	
PELLET	i.	Temperature: 25°C
	ii.	Pressure: 1 bar
	iii.	Mass flowrate: 5 kg/s
	iv.	Valid phases: Vapor-liquid
AIR	i.	Temperature: 25°C
	ii.	Pressure: 1 bar
	iii.	Mass flowrate: 37.5 kg/s
	iv.	Mole fraction: 0.79 (Nitrogen) and 0.21 (Oxygen)
	v.	Valid phases: Vapor-liquid
H2O-IN	i.	Temperature: 25°C
	ii.	Pressure: 2 bar
	iii.	Mass flowrate: 11.5 kg/s
	iv.	Valid phases: Vapor-liquid
	v.	Mole fraction: 1

2.4. Simulate, validate and analyse the result

Firstly, the components involved were defined in the properties section of Aspen Plus by using Peng Robinson equation of state as property method. Based on Figure 3, the process was divided into two routes before entering the heat exchanger which were from a boiler and a heater. The combination of the boiler and heat exchanger represent a water tube boiler in Aspen Plus as there was no direct water tube boiler system in the software. In the first route, there were two inlet streams entering the boiler which were torrefied EFB pellet as fuel and air for oxygen supply in the combustion reaction of the pellet. The pellet stream entered at 25°C and 1 bar before heated to 250°C with a heater. The composition of elemental component of torrefied EFB was defined based on its ultimate analysis composition at 250°C as shown in Table 2.

Table 2. Composition of torrefied EFB pellet (wt%) [10]

Sample	C	H	N	S	O
Torr 250	49.47	5.91	0.52	0.54	43.56

Next, the pellet and air entered a boiler which in this case, a stoichiometric reactor was used (BOILER). The reactor operated at 736°C and 45 bar with vapor-liquid as its valid phases to produce a superheated steam of 45 bar at 451°C which was the same as in the base case study. The combustion equations for feed components such as carbon, hydrogen, sulphur, nitrogen and nitric oxide were listed below respectively and the reactions were defined under the section "Reactions" of stoichiometric reactor. It was assumed that the conversion for carbon and hydrogen were the same which was 80% while sulphur, nitrogen and nitric oxide had a conversion of only 10%.

$$C + O_2 \rightarrow CO_2 \tag{1}$$
$$2H_2 + O_2 \rightarrow 2H_2O \tag{2}$$
$$S + O_2 \rightarrow SO_2 \tag{3}$$
$$N_2 + O_2 \rightarrow 2NO \tag{4}$$
$$2NO + O_2 \rightarrow 2N0_2 \tag{5}$$

Then, the combusted gas produced entered a heat exchanger (BL-TUBES) which represent water tubes in water tube boiler and the combusted gas was connected to the hot inlet of the heat exchanger. A shortcut, counter current heat exchanger was used with a minimum temperature approach of 1°C while the hot stream outlet temperature was at 100°C. In the pressure drop section, outlet pressure of 45 bar was assumed in order to produce a high pressure steam. Simultaneously, a water inlet stream operated at 25°C and 2 bar was pumped to a pressure of 45 bar which was then connected to a heater (HEATER2) to be heated to 98°C before entering the heat exchanger as its cold inlet. The exhaust gas from the hot outlet stream of the heat exchanger was released. Meanwhile, the cold outlet stream of the heat exchanger which was labelled as SH-STEAM became a superheated steam which was then connected to a back-pressure steam turbine for power and heat production. The steam turbine (TURBINE) was assumed to be an isentropic turbine. According to Qibai Wu et.al, the steam turbine operated at 3.5 bar with 50% efficiency. The electricity generated was transferred to the main switch box for power distribution while exhaust gas was sent to a steam manifold for the plant's heating purposes. Once the simulation converged, the results were analysed and compared with the power output of the chosen published journal to validate the developed process. Further discussions were also made.

2.5. Improve further the cogeneration process through optimization
Optimization methods were analysed and selected by considering feasibility aspect of the available data. Two types of optimization method were selected and conducted to improve the model by applying parametric optimization and structural optimization.

2.6. Conduct parametric optimization from simulation model and analyse the results
Parametric optimization was conducted to measure the performance of the model and also to optimize the selected parameters such as pellet flow rate, water flow rate, air flow rate and boiler temperature. Comparison between the parameters and power generated were made and analysed.

2.7. Conduct structural optimization by using GAMS and analyse the results
Structural optimization was carried out in GAMS in order to choose the optimum structural design of the model by optimizing the correct combination of structural options. Five options with different structural design were modelled in Aspen Plus beforehand with each of the options had its own strength and weakness. The options are as follow:

- Option 1: Cogeneration process with installed air preheater and low pressure steam production
- Option 2: Cogeneration process with steam turbine stages and low pressure steam production

- Option 3: Cogeneration process with installed air preheater and medium pressure steam production
- Option 4: Cogeneration process with steam turbine stages and medium pressure production
- Option 5: Cogeneration process without installed steam turbine and only focused in medium pressure steam production

Next, the processing cost of each options were calculated by using equation (6).

$$COM = 0.18FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \tag{6}$$

Where C_{OM} is cost of manufacturing, F_{CI} is fixed capital investment, C_{OL} is cost of operating labor, C_{WT} is cost of waste treatment and C_{RM} is cost of raw material [5]. Before formulation was conducted, few parameters, decision variables, constraints and objective function were identified.

2.7.1. Parameters. The parameters identified were medium pressure steam price, low pressure steam price, raw material cost, processing cost to produce 1 kg of steam and processing cost to produce 1 kWh of power.

2.7.2. Decision variables. Below are the list of decision variables:

- x_1 : Power production from option 1
- x_2 : Low pressure steam flowrate production from option 1
- x_3 : Power production from option 2
- x_4 : Low pressure steam flowrate production from option 2
- x_5 : Power production from option 3
- x_6 : Medium pressure steam flowrate production from option 3
- x_7 : Power production from option 4
- x_8 : Medium pressure steam flowrate production from option 4
- x_9 : Medium pressure steam flowrate production from option 5

Binary variables were termed as “0-1” where 0 indicates rejection of the variable while 1 indicates the acceptance of the variable [11]. Below are the list of binary variables:

- y_1 : Binary for power production from option 1
- y_2 : Binary for low pressure steam flowrate production from option 1
- y_3 : Binary for power production from option 2
- y_4 : Binary for low pressure steam flowrate production from option 2
- y_5 : Binary for power production from option 3
- y_6 : Binary for medium pressure steam flowrate production from option 3
- y_7 : Binary for power production from option 4
- y_8 : Binary for medium pressure steam flowrate production from option 4
- y_9 : Binary for medium pressure steam flowrate production from option 5

2.7.3. Constraints. The power production was assumed to be 1400 kW and steam flowrate production for both low pressure and medium pressure steam were assumed to be 41400 kg/h. This value constraints were based on the minimum output value simulated from previous Aspen Plus model. The constraints are as below:

$$x_1 + x_3 + x_5 + x_7 = 1400 \tag{7}$$
$$x_2 + x_4 + x_6 + x_8 + x_9 = 4140 \tag{8}$$
$$y_1 + y_3 + y_5 + y_7 = 1 \tag{9}$$
$$y_2 + y_4 + y_6 + y_8 + y_9 = 1 \tag{10}$$

2.7.4. Objective function. Objective function of the study was to maximise the profit of the plant per year where profit can be calculated as in equation (11).

$$Profit_i = Revenue_i - Processing\ Cost_i \tag{11}$$

Where i can be stated as power, medium pressure steam or low pressure steam. Equation (12) is obtained after calculating the profit for each options.

$$125872.14x_1y_1 + 98127.59x_2y_2 + 135018.37x_3y_3 + 98126.4x_4y_4 + 44102.88x_5y_5 + 103012.4x_6y_6 + 74361.22x_7y_7 + 103011.2x_8y_8 + 103013.6x_9y_9 = profit \quad (12)$$

2.7.5. Optimization method. Mixed integer nonlinear programming (MINLP) was formulated where it refers to optimization problem involving continuous and discrete variables and also nonlinear functions in the objective function or the constraints. MINLP can be used to simultaneously optimize the system structure which is a discrete variable and parameter which is a continuous variable [4]. Discrete and Continuous Optimizer (DICOPT) was used as a solver and the data obtained from GAMS was analysed.

3. Results and discussions

3.1. Aspen Plus model of biomass-based cogeneration plant

From the simulation, 1.764 MW of power and a low pressure steam of 4 bar were generated from the turbine which was lower compared to the base case study where 2.2 MW of power generated by using ECLIPSE software. This differences may be due to optimization was carried out beforehand for the base case study while Aspen Plus model had not yet undergone optimization. However, 1.764 MW of power generated from Aspen Plus still exceeded the actual need of electricity for the mill which was 1.3MW. Thus, the plant can produce more than enough electricity and steam for the production process when torrefied EFB pellet was used as fuel. The additional electricity can be sold to the national power grid. Thus, the old and conventional fossil fuel plants can be replaced by renewable and environmental friendly plants which use torrefied EFB as fuel. Besides, the dependency and demand towards fossil fuels can be reduced and minimized the environmental degradation.

3.2. Parametric optimization from Aspen Plus model

The results of the modifications from parametric optimization are shown in Table 3 until Table 7.

Table 3. The value of power generated at certain pellet flow rate

Pellet Flow Rate (kg/s)	2	3	4	5
Power Generated (MW)	1.347	1.458	1.599	1.764

Table 4. The value of power generated at certain water flow rate

Water Flow Rate (kg/s)	11.5	12.0	12.5	13.0	13.5
Power Generated (MW)	1.764	1.689	1.631	1.591	1.569

Table 5. The value of power generated at certain air flow rate

Air Flow Rate (kg/s)	34.5	35.5	36.5	37.5	38.5	39.5
Power Generated (MW)	1.558	1.622	1.691	1.764	1.841	1.920

Table 6. The value of power generated at certain boiler temperature (Continued)

Temperature (^{O}C)	660	680	700	720	740	760	780	800	820
Power Generated (MW)	1.387	1.469	1.564	1.671	1.789	1.916	2.043	2.170	2.296

Table 7. The value of power generated at certain boiler temperature (Continued)

Temperature (^{O}C)	840	860	880	900	920	940	960	980
Power Generated (MW)	2.421	2.545	2.668	2.790	2.912	3.033	3.152	3.271

The results show that the initial pellet flow rate and water flow rate should be maintained at 5 kg/s and 11.5 kg/s respectively to generate maximum power. Furthermore, 37.5 kg/s of initial air flow rate can be increased to 39.5 kg/s and the temperature of the boiler should be increased for a maximum power generation. Meanwhile, the pattern of each modifications can be seen in Figure 4 until Figure 7.

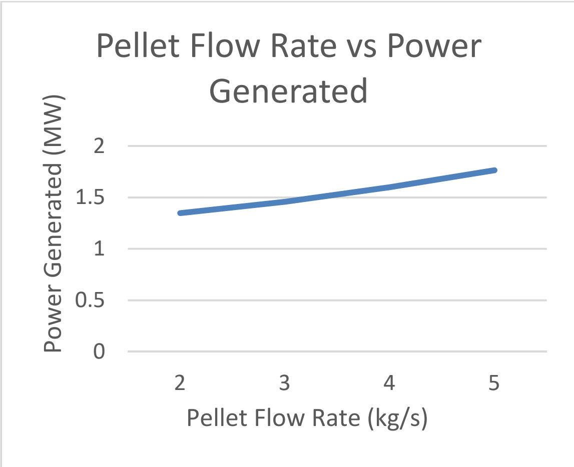

Figure 4. Graph of pellet flow rate against power generated

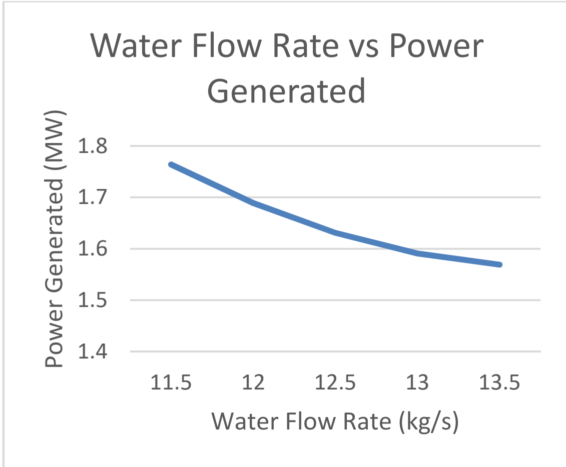

Figure 5. Graph of water flow rate against power generated

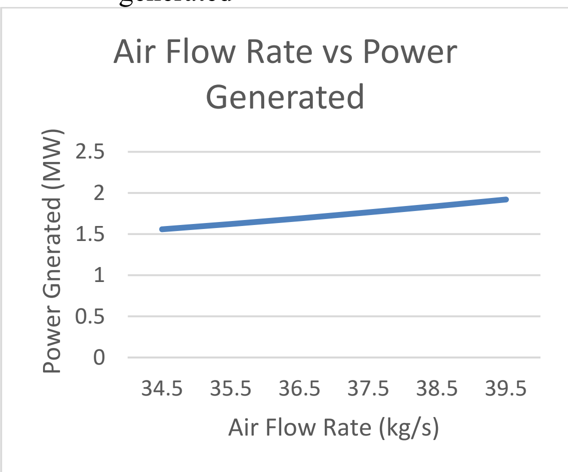

Figure 6. Graph of air flow rate against power generated

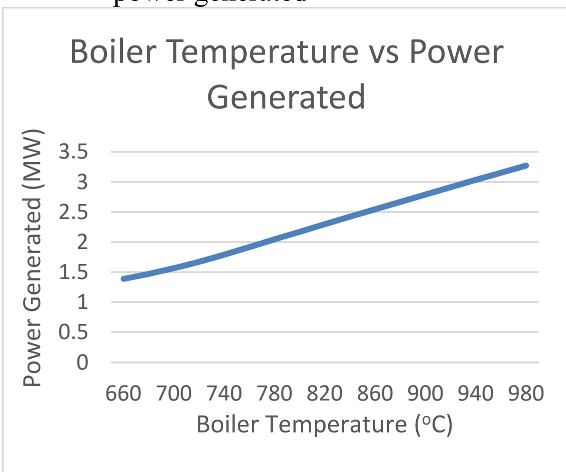

Figure 7. Graph of boiler temperature against power generated

It can be seen that power generated increases as pellet flow rate increases, water flow rate decreases, air flow rate increases and boiler temperature increases. This may be due to the factor of reaction rate where higher temperature will lead to higher kinetic energy and larger amount of molecules possess the required activation energy thus, an increase in the effective collisions between particles [12]. Besides, more fuel to be acted upon the air for combustion reaction increases the reaction rate. However, beyond 5 kg/s of EFB pellet resulted in infeasibility of the model as air became its limiting reactant. Furthermore, reduction in water flow rate was favourable to increase power generated as more heat can be supplied to heat the water which increases the temperature of steam produced and simultaneously increases the work done by the turbine. Moreover, higher air flow rate lead to a near complete combustion reaction and low production of incomplete combustion gases as amount of oxygen supply increases [13].

3.3. Structural optimization results from GAMS

The optimization results from GAMS accepted the binary variable of y_3 and y_6 while others were rejected. It was also shown that a profit of RM4,453,739,078.00 can be achieved if the plant operates to produce power and medium pressure steam at 1400 kW and 41400 kg/h respectively. However, the profit obtained was too high and might be unrealistic to achieve in real case study. This may be due to the range of constraints applied were too large for the process and it was not enough to reduce the boundary of steam and power production as reduction in the boundary values can lead to a more accurate and realistic data. Thus, further refinement should be made in the future in order to reduce the scope of the constraints and to apply more restriction towards the process.

4. Conclusions and recommendations

It can be concluded that the simulation of cogeneration plant by using torrefied EFB pellet as fuel in Aspen Plus was able to produce power of greater than 1.3 MW and optimization procedures helped in deciding the optimum value for parameters and also in the selection of production where power and medium pressure steam were favourable. Thus, biomass-based cogeneration plant has a great potential to replace the current technologies which is mostly using conventional fossil fuels. This findings are significant as it could reduce the carbon emission which can lead to a greener and healthier environment for electrical power generation sector. This research can be further improved by taking into consideration of few parameters such as raw materials' availability and products' demand in order to achieve more accurate and reliable optimal results.

5. References

[1] S. Mekhilef, R. Saidur, A. Safari, and W. E. S. B. Mustaffa, "Biomass energy in Malaysia: Current state and prospects," *Renew. Sustain. Energy Rev*., vol. 15, no. 7, pp. 3360–3370, 2011.
[2] A. Darabadi Zareh, R. Khoshbakhti Saray, S. Mirmasoumi, and K. Bahlouli, "Extensive thermodynamic and economic analysis of the cogeneration of heat and power system fueled by the blend of natural gas and biogas," *Energy Convers. Manag*., vol. 164, no. March, pp. 329–343, 2018.
[3] T. H. Oh, M. Hasanuzzaman, J. Selvaraj, S. C. Teo, and S. C. Chua, "Energy policy and alternative energy in Malaysia: Issues and challenges for sustainable growth – An update," *Renew. Sustain. Energy Rev*., vol. 81, no. July 2017, pp. 3021–3031, 2018.
[4] L. S. L. Thomas F. Edgar, David M. Himmelblau, Optimization of Chemical Process. 2001.
[5] T. and Richard and W. B, *Analysis, Synthesis, and Design of Chemical Process*, Third Edit. 2009.
[6] N. Abdullah and F. Sulaim, "The Oil Palm Wastes in Malaysia," *Biomass Now - Sustain. Growth Use*, no. December, 2013.
[7] C. Y. Ket, "Optimization on Acrylic Acid Plant by Using Aspen Plus," University of Malaysia Pahang, 2013.
[8] G. D. Corporation, "GAMS – Documentation," no. October, 2018.
[9] Q. Wu, T. C. Qiang, G. Zeng, H. Zhang, Y. Huang, and Y. Wang, "Sustainable and renewable energy from biomass wastes in palm oil industry: A case study in Malaysia," *Int. J. Hydrogen Energy*, vol. 42, no. 37, pp. 23871–23877, 2017.
[10] B. Bevan, A. Ahmad, A. Johari, T. Amran, and T. Abdullah, "Torrefaction of Pelletized Oil Palm Empty Fruit Bunches," *21st Int. Symp. Alcohol Fuels – 21st ISAF*, pp. 15–19, 2015.
[11] H. Ausen, "A Study in MINLP-class Optimization Problems for Simulated Petroleum Production," no. June, 2012.
[12] W. L. Masterton, "Rate of Reaction," in *Chemistry: Principles and Reactions*, 8th ed., Belmont, CA Brooks Cole, Cengage Learning 2009, 2015, p. 274.
[13] H. Biteau, A. Fuentes, G. Marlair, and J. L. Torero, "The influence of oxygen concentration on the combustion of a fuel/oxidizer mixture," *Exp. Therm. Fluid Sci*., vol. 34, no. 3, pp. 282–289, 2010.

Acknowledgements

The authors would like to acknowledge Universiti Malaysia Pahang (UMP) under the research grant of RDU 1703170 and the Faculty of Chemical and Natural Resources Engineering for the financial support and opportunity in conducting this research.