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Design of Biomass Combined Heat and Power (CHP) Systems based on Economic Risk using Minimax Regret Criterion

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Abstract. It is a great challenge to identify optimum technologies for CHP systems that utilise biomass and convert it into heat and power. In this respect, industry decision makers are lacking in confidence to invest in biomass CHP due to economic risk from varying energy demand. This research work presents a linear programming systematic framework to design biomass CHP system based on potential loss of profit due to varying energy demand. Minimax Regret Criterion (MRC) approach was used to assess maximum regret between selections of the given biomass CHP design based on energy demand. Based on this, the model determined an optimal biomass CHP design with minimum regret in economic opportunity. As Feed-in Tariff (FiT) rates affects the revenue of the CHP plant, sensitivity analysis was then performed on FiT rates on the selection of biomass CHP design. Besides, design analysis on the trend of the optimum design selected by model was conducted. To demonstrate the proposed framework in this research, a case study was solved using the proposed approach. The case study focused on designing a biomass CHP system for a palm oil mill (POM) due to large energy potential of oil palm biomass in Malaysia.

1 Introduction

Global energy demands are projected to increase 48% from 2012 by 2040 [1, 2]. To meet this projected increase in energy demand, biomass energy is expected to play an imperative role over the coming years. In fact, global biomass energy demands from 2000 to 2015 have seen a significant increase as compared to stable hydropower demands [3]. Such increase indicates that biomass is gaining attention in the renewable energy market. Biomass can be categorised into lignocellulose biomass, municipal waste and animal manure. These biomass resources can be obtained from agricultural residues, biomass plantations and organic wastes from residential areas [4]. Approximately 70% of these

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biomass are lignocellulosic biomass from plantations such as cereal, oil and sugar crops [5]. Intergovernmental Panel on Climate
Change Special Report on Renewable energy (IPCC-SRREN) reported that solely on biomass from plantations are estimated to have potential energy up to 700 x 10^{12} MJ/year whereas other sources of biomass such as food and municipal waste had only 300 x 10^{12} MJ/year of potential energy [4]. Due to the high availability of lignocellulose biomass, recent studies on biomass utilisation focus on converting biomass into bioenergy and biofuels.

In Malaysia, one major source of lignocellulose biomass is oil palm biomass from the palm oil industry which provides approximately 82.61wt% of total biomass in Malaysia [6]. The palm oil industry generates biomass such as empty fruit bunches (EFBs), palm mesocarp fibre (PMF), palm kernel shell (PKS) and palm oil mill effluent (POME). These oil palm biomass are wastes produced during the extraction of crude palm oil (CPO) and crude palm kernel oil (CPKO) from fresh fruit bunches (FFB). Based on Malaysia Palm Oil Board [7], amount of FFB processed in Malaysia palm oil mill in 2016 is approximately 60 million tonnes. Solid oil palm biomass such as EFB, PMF and PKS are generated at about 28.42 million tonnes while POME is produced at about 40.04 million tonnes during palm oil extraction annually in 2017 [6–8]. These biomass have high calorific value that can be converted into heat and power using biomass combined heat and power (CHP) systems. This provides an opportunity for the industry to harness high amount of bioenergy from sources that were initially disposed as waste by-products.

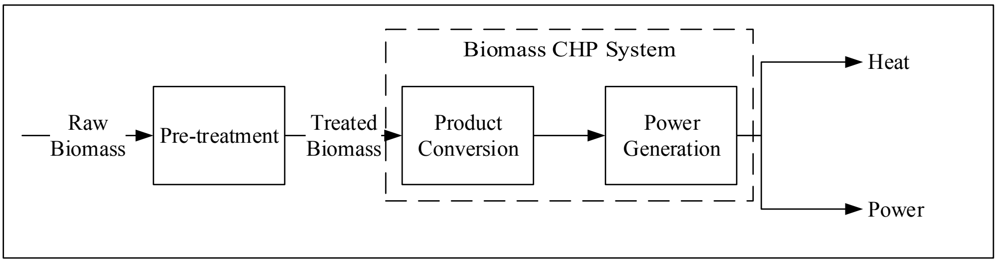

Fig. 1.1. Simple Illustration of Biomass CHP system

Figure 1.1 above illustrates a biomass CHP is a system to generate power and thermal energy from biomass sources for industrial and/or residential needs [9]. A biomass CHP system commonly consists of pre-treatment unit, product conversion unit and power generation unit. Pre-treatment units such as shredder and dryer are required to reduce size and moisture content in biomass to allow efficient conversion into products through conversion units such as (but not limited to) boilers, gasifiers, digesters [6, 10, 11]. Biomass undergoes combustion in boilers to produce steam where steam produce can be used to produce energy using a steam turbine. Gasifiers convert biomass into syngas and digesters convert biomass into biogas. Syngas consists of carbon monoxide and hydrogen that could be combusted in gas engines, gas turbines and micro-turbines. Similarly, biogas consist of mostly methane gas can be combust in similar power generation units to produce power [10, 11].

The Malaysian government had announced a program known as Small Renewable Energy Power (SREP) program back in 2001 to encourage industrial players to utilise agricultural wastes to generate power. With support from United Nation Development Programme and Global Environment Facility and SREP, the first demonstration of 13 MW CHP plant using EFB was built in Bahau, Negeri Sembilan [8]. Currently in Malaysia, most palm oil mills have CHP plants installed to meet internal energy demands. However, the power generated from these CHP plants are insufficient to supply to national power grid. This is due to some challenges met by these power plants that was outlined by several work from Umar et. al.[11–13] and it is summarised as following.

- Varying energy demand and biomass supply – Subjected to energy demand, palm oil mill will have sufficient biomass supply to meet energy demand for operation of the palm oil mill. However, feeding any power generated to national grid will have difficulties to ensure stable supply of biomass to fed into CHP systems due to seasonal nature of palm oil production to cope with varying energy demand.

- Non-favourable government program and schemes – SREP and Feed-in-Tariff (FiT) had proposed by the government in hope of palm oil mill owners to utilise their oil palm biomass to generate electricity and feed into gridlines. However, respondents from these work expressed that current FiT rates are not attractive enough to them. Hence, most of the power generated from biomass CHP plant were used for self-consumption in palm oil mill instead of feeding it into power grid.

- Location of palm oil mill from gridlines – Approximately 62.3% of palm oil mills in Malaysia are situated at least 10 km from any electricity network system. Connecting these CHP systems in palm oil mill to the gridlines requires intensive amount of capital cost. A heuristic value regarding cost required for connection of grid is given as approximately RM 1 to 1.5 million per km of gridline [14]. Hence, palm oil mill owners are reluctant to invest such capital cost when there are risk of having unstable power generation with varying biomass supply.

- Perspective of palm oil mill owner – Respondents considers biomass energy systems as a highly intensive capital invest with long payback period. Since the palm oil industry focuses on edible oil production as their main traditional business, most mill owners prefer not to risk participating in the renewable energy industry. Furthermore, mill owners have expressed that challenges in financial capability to participate in such capital-intensive projects.

Due to uncertainty of biomass supply in meeting varying energy demands, palm oil mill owner possess a lack confidence to invest in a capital-intensive biomass CHP system. Others factors such as distance of palm oil mill from gridlines and unattractive government subsidy or tariff programs contribute further to this lack of confidence. Therefore, there is a need of a framework to design CHP system that cope with varying energy demands and subsequently provides an optimal design with low economical risk in order to gain confidence from palm oil mill owners.

In a similar area of research, several research works have been proposed to analyse economic risk of renewable energy technologies (RET) using an approach known as Monte Carlo Simulation (MCS) approach. MCS considers uncertainty in variables behaviour through probability distribution to quantify the possibility of a certain condition will occur [15]. Arnold et al. [16] assessed economical risk for renewable energy infrastructures using

MCS to compare different boundary conditions such as climate, capital and operating cost. However, it is stated by the author that this MCS model requires a matching tool to select suitable RET for each case study of interest. In addition, Edinaldo et al. [15] presented a similar mathematical model to help in justifying whether the selected RET is worth investing through MCS approach. However, MCS approach used in both Arnold and Edinaldo's work only analyses a certain RET potential economic risk without providing clear suggestion on selection of optimal RET. Therefore, there is a need for a framework that is able to analyse potential economic risk and subsequently synthesise an optimal RET system.

Recent studies by Yokoyama [17, 18] used Minimax Regret Criterion (MRC) approach to evaluate economic risk and subsequently providing optimal design of energy supply system. However, Yokoyama's study only focuses on conventional energy supply system. Besides, challenges faced in utilising biomass CHP such as varying biomass supply and energy demand were not addressed in recent work. Therefore, in this work, a mathematical optimisation model was developed to synthesise an optimal design for biomass CHP systems based on potential loss of profitable opportunity using MRC approach at varying energy demand. The objective of this developed framework are as follows:

1. To determine the optimal design for the biomass CHP system based on maximum gross profit.
2. To assess potential economy risk for a given biomass CHP design based on varying energy demand using MRC approach.

Such model will enable designers to systematically design a biomass CHP with minimal economic risk using MRC approach.

2 Methodology

As described previously, a mathematical model framework was developed to design an optimal biomass CHP system to meet certain energy demand with minimal economic risk through Minimax Regret Criterion (MRC) approach. A case study based on palm oil mill biomass was conducted using the framework generated. To carry out the case study, a palm oil mill case study superstructure was developed to show possible biomass CHP designs to convert palm oil mill biomass into heat and power. With the superstructure developed, mathematical model equations were formulated for each biomass CHP technology unit. These equations correlates biomass mass flow rates, efficiency of CHP systems, heat and power produced and capital expenditure (CAPEX) of equipment. The mathematical model will ultimately provide biomass CHP design based on maximum gross profit at different energy demands. Following this, MRC approach was utilised to select the optimum biomass CHP design which has the lowest maximum regret value. The term "maximum regret value" is defined as the as maximum amount of profitable opportunity loss by making a wrong decision in design [19]. A sensitivity analysis of Feed-in Tariff (FiT) rates on selection of optimum biomass CHP design was conducted to analyse the impact of the change of FiT rates on the selection for optimum design of biomass CHP. Lastly, design analysis on optimum biomass CHP design was conducted to study the trend of selection for biomass CHP design by the framework base on case study.

2.1 Generic Superstructure of Biomass CHP Design

Resources i represents biomass supply with flow rates F_i can be used to convert into product $p \in P$ through technology $j \in J$. The product p can be further converted to energy $e \in E$ via power generation technology $j' \in J'$. Figure 2.1 below shows the generic superstructure of Biomass CHP design. With the generic superstructure, equations formulated in the following sections are based on Figure 2.1.

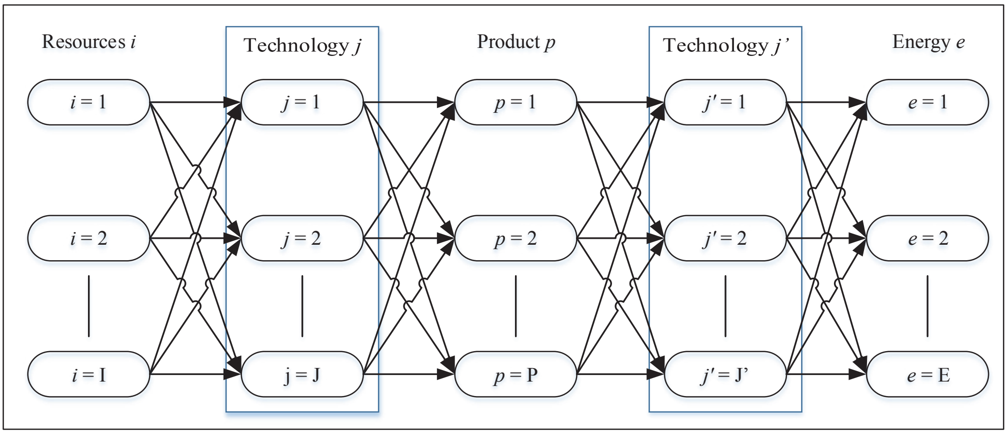

Fig 2.1. Generic Case Study Superstructure

2.2 Mathematical Model Equations

Referring to Figure 2.1, following mathematical modelling equations were formulated based on data collected for the respective process unit to convert biomass to heat and power. Mass and energy balance equation was developed first for each biomass CHP system to convert biomass to heat and power. Following this, the equation for capital expenditure (CAPEX) of each equipment was developed based on the equipment capacity parameters such as flow rates and energy produced. With CAPEX of equipment and energy production equations, the optimum biomass CHP design that provide maximum gross profit was generated using LINGO programming software. The data of gross profit and optimum biomass CHP design at different power demand will be utilised in Minimax Regret Criterion (MRC) approach to solve for optimum biomass design that provide maximum gross profit with minimal economical risk.

2.2.1 Mass and Energy Conversion Mathematical Equations

Eq. (1) shows the component balance for biomass i where f_i and x_i are the component mass flow rates and composition respectively based on Figure 2.1 where F_i represents the total flow rate of biomass i.

$$f_i = F_i x_i \qquad \forall i \qquad (1)$$

Biomass i is allocated to potential technology j as shown in in Eq. (2) where F_{ij} is the flow rate entering technology j.

$$F_i=\sum_{j=1}^{J} F_{ij} \qquad \forall i\forall j \qquad (2)$$

Technology j converts entering biomass F_{ij} into product p. Eq. (3) shows the conversion of F_{ij} into mass flow rate of product F_{jp} with a conversion factor of k_{jp} for each technology.

$$F_{jp}=k_{jp}F_{ij} \qquad \forall i\forall j\forall p \qquad (3)$$

Total rate of production for product p for all technologies j is shown as Eq. (4).

$$F_p=\sum_{j=1}^{J} F_{jp} \qquad \forall j\forall p \qquad (4)$$

The product p is then distributed to power generation technology j' to convert into energy e. The distribution of product p is as shown in Eq. (5).

$$F_p=\sum_{j'=1}^{J'} F_{pj'} \qquad \forall j'\forall p \qquad (5)$$

Eq. (6) shows distributed product p converts into power $E_{j'e}$ through power generation technology j'. $n_{j'p}$ is the conversion efficiency of each power generation technology j'.

$$E_{j'e}=n_{j'p}F_{pj'} \qquad \forall e\forall j'\forall p \qquad (6)$$

The total power generated by technologies j' is calculated as Eq. (7) below.

$$E_T=\sum_{e=1}^{E} E_{j'e} \qquad \forall e\forall j' \qquad (7)$$

2.2.2 Capital Expenditure (CAPEX) of Equipment Mathematical Equations

The capital expenditure (CAPEX) equations of each technologies shown in Figure 2.1 were formulated based on data collected. CAPEX of each technologies C_j and $C_{j'}$ are determined via Eq. (8) and (9). k_{cj} and $k_{cj'}$ are the cost factor of each technologies correlated to its technology size factor M_j and $M_{j'}$ respectively. Example of size factor M_j are flow rates through the equipment (F_{ij} or F_{jp}) and power capacity of the equipment $E_{j'e}$.

$$C_j=k_{Cj}M_j \qquad \forall j \qquad (8)$$
$$C_{j'}=k_{Cj'}M_{j'} \qquad \forall j' \qquad (9)$$

The total capital expenditure (CAPEX) of the technologies is as shown in Eq. (10).

$$CAPEX=\sum_{j=1}^{J} C_j+\sum_{j'=1}^{J'} C_{j'} \qquad \forall j\forall j' \qquad (10)$$

2.2.3 Solving Case Study by Minimax Regret Criterion (MRC) Approach

With the total *CAPEX* of equipment and energy produced from biomass CHP design calculated using Eq. (10), gross profit based on energy produced through CHP system were calculated with power tariff data at the location of the palm oil mill. Eq. (11) below shows the gross profit P_{gross} calculation of the CHP system. AOT is the annual operation time of the plant and (A/P) is the capital recovery compound interest factor for uniform payment of the biomass CHP plant.

$$P_{gross}=E_T \times Tariff \times AOT - CAPEX \times (A/P) \quad (11)$$

By maximising gross profit from Eq. (11) at different power demand, the data of gross profit are subsequently used in Minimax Regret Criterion (MRC) approach to decide on the optimum design of biomass CHP with minimal regret. The term "regret" refers to a quantifiable value on loss of profitable opportunity due to a decision made in design. For example, if the design selected have much higher power capacity than the power demand, the biomass CHP plant will be running on low capacity which will generate lower gross profit than its potential gross profit. MRC approach is commonly used in business and finance model to make decision that minimises the possible maximum regret [13, 18]. Generic tables used for MRC approach are shown in Table 2.1 and 2.2 below.

Table 2.1. Generic gross profit table used for MRC approach

Factor 1	Factor 2		
	j_1	j_2	j_3
i_1	P_{11}	P_{12}	P_{13}
i_2	P_{21}	P_{22}	P_{23}
i_3	P_{31}	P_{32}	P_{33}

Where i_n is the levels of factor 1, j_n is the levels of factor 2 and P_{ij} as stated in the table are the gross profit of the system.

Table 2.2. Generic Regret Table used for MRC approach

Factor 1	Factor 2			Maximum Regret Value
	j_1	j_2	j_3	
i_1	R_{11}	R_{12}	R_{13}	$R_{max,1}$
i_2	R_{21}	R_{22}	R_{23}	$R_{max,2}$
i_3	R_{31}	R_{32}	R_{33}	$R_{max,3}$

Where R_{ij} is the regret value of each level combination of the factors and $R_{max,i}$ is the maximum regret value of each row.

The MRC approach calculations based on Table 2.1 and 2.2 with $i = 1, 2, 3 \ldots, I$ and $j = 1, 2, 3\ldots, J$ are as following:

For gross profit table,

1. $P_{i,j}$ is gross profit calculated with Eq. (11) at energy demand and capacity of the CHP designed are equal to each other. (diagonal row of the table from top left to bottom right)
2. $P_{i,i+j}$ are equal to $P_{i,j}$ since the profit is limited by the maximum capacity of the CHP designed where energy demand is more than designed CHP capacity. (columns on top of diagonal row of the table)
3. $P_{i+j,j}$ is calculated with Eq.(11) at energy demand is lesser than capacity of CHP designed. (Columns below of diagonal row of the table)

For regret value table,

1. $R_{i,j}$ (diagonal row from top left to bottom right) equal to zero since energy demand occurred is equal to capacity of CHP designed.
2. $R_{i,i+j}$ (columns on top of diagonal row of the table) are calculated by Eq. (12).

$$R_{i,i+j}=P_{i+j,i+j} - P_{i,i} \tag{12}$$

3. $R_{i+j,j}$ (columns below of diagonal row of the table) are calculated by Eq. (13)

$$R_{i+j,j}=P_{i+j,j} - P_{j,j} \tag{13}$$

4. Determine the maximum regret value for each row.
5. Select the design criteria with the smallest maximum regret value.

2.3 Palm Oil Mill Case Study Superstructure

Figure 2.2 below shows the palm oil mill case study superstructure developed for the mathematical model.

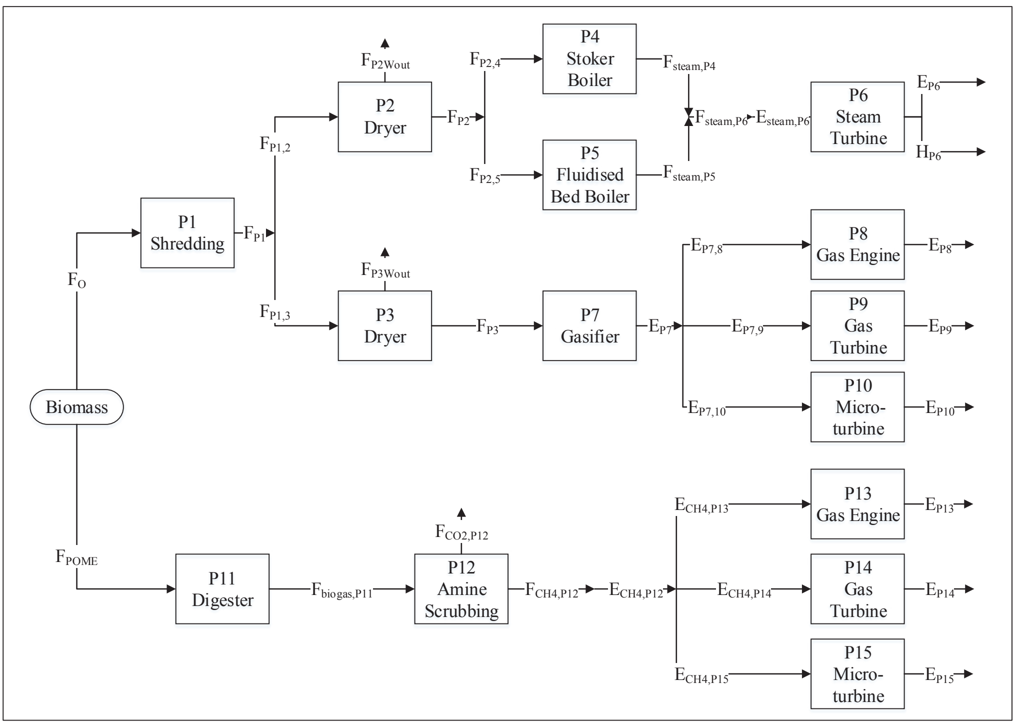

Fig. 2.2. Palm Oil Mill Case Study Superstructure

The amount of biomass supply for this case study is taken as 10000 kg/hr of mix solid biomass and palm oil mill effluent (POME) of 10 m^3/day. Varying the power demand as the manipulating variable, power demand range from 250 kW to 13 MW were input into the model to identity the optimum biomass CHP technology pathway.

2.4 Sensitivity Analysis of Feed-in Tariff (FiT)

Feed-in tariff (FiT) system is a distributed premium license to individual or company to legally sell renewable energy at the FiT rate to companies that distribute electricity [20]. FiT rates for power generation using biogas and solid biomass are different rates. Basic FiT rates varies with installed capacity and bonus FiT rates applies when certain criteria of the installed CHP technology is met. To ease the calculation in sensitivity analysis, the FiT rates used to calculate the gross profit of CHP plant was taken as average of RM 0.2985 per kWh for biomass power generation and RM 0.2886 per kWh for biogas power generation [20]. For the sensitivity analysis conducted, the FiT rates are changed at ±10, ±30 and ±50% from its original tariff. The purpose of doing this is to analyse the impact of the change of FiT rates on the selection for optimum design of biomass CHP technologies.

2.5 Analysis of Optimum Biomass CHP Design

Optimum biomass CHP design that are recommended by model through maximising gross profit at varying power demand for the case study was analysed to study the trend of optimum selection for biomass CHP design. Besides, the analysis identifies which biomass CHP design is compulsory across a certain range of power demand. These "must-have" design is compulsory to have in order to achieve the required power demand. The analysis also identifies "optional" equipment that can be invested in if process designers are ambitious to meet higher power demands and equipment that are never selected throughout the power demand range appear as a "must-avoids". This analysis helps plant designers to narrow down their selection of biomass CHP design and subsequently decide on the optimum selection of biomass CHP design.

3 Results and Discussion

As described previously, the methodology for this work was carried out to determine an optimum biomass CHP design for palm oil mill using Minimax Regret Criterion (MRC). In this section, the results obtained from the case study are analysed and discussed. Following this, a sensitivity analysis on Feed-in Tariff (FiT) rates was performed to analyse the impact of FiT rates on the selection of biomass CHP design. Lastly, a design analysis was done on the optimum design of biomass CHP to study the trend of recommended design by the mathematical model. In the design analysis, "must-have", "optional" and "must-avoid" designs were identified to ease plant designer decision on selecting the optimum selection of biomass CHP design.

3.1 Optimum Biomass CHP Design using MRC Approach

To select the optimum design of CHP plant throughout the wide range of power demand, Minimax Regret Criterion (MRC) approach was utilised as described in methodology. Taking the power demands are 3000, 5000, 8000 and 10000 kW, Table 3.1 below shows the gross profit table of optimum biomass CHP designs at different power demand.

Table 3.1. Gross Profit Table of Case Study in unit RM/year

Designed Capacity (kW)	Power Demand (kW)			
	3000	5000	8000	10000
3000	4,470,740.00	4,470,740.00	4,470,740.00	4,470,740.00
5000	1,481,316.30	6,154,717.00	6,154,717.00	6,154,717.00
8000	(2,213,380.58)	2,460,019.42	9,964,220.00	9,964,220.00
10000	(3,897,126.95)	776,273.05	8,280,473.05	12,938,480.00

As shown in Table 3.1, values in parentheses represent loss of profit. The mathematical model provided the biomass CHP design at its respective designed capacity. The equipment that were selected while the gross profit of biomass CHP design is maximised will have CAPEX value shown in the mathematical model while solving gross profit for each designed capacity. Hence, the biomass CHP design for each designed capacity identified are listed below in Table 3.2.

Table 3.2. Biomass CHP Design at each Designed Capacity

Biomass CHP Design	Plant Power Capacity (kW)
Biogas with GE	3000
Syngas + Biogas GE	5000
Boiler with Steam Turbine	8000
Combined Boiler with Steam Turbine and Biogas with GE	10000

The regret table was developed to identify the maximum regret value of each biomass CHP technology. The biomass CHP technology with the smallest value between the maximum regret values was selected as the optimum biomass CHP technology. The regret table was developed as below.

Table 3.3. Regret Table of Case Study in unit RM/year

Designed Capacity (kW)	Power Demand (kW)				Max Regret Value
	3000	5000	8000	10000	
3000	-	1,683,977	5,493,480	8,467,740	8,467,740
5000	2,989,423	-	3,809,503	6,783,763	6,783,763
8000	6,684,120	3,694,697	-	2,974,260	6,684,120
10000	8,367,866	5,378,443	1,683,746	-	8,367,866

Selecting the smallest maximum regret value in Table 3.3, the optimum design capacity of biomass CHP plant is 8000 kW. Based on Table 3.2, the optimum biomass CHP technology at 8000 kW is steam generation using boiler with steam turbine to generate power. Therefore, boiler with steam turbine power generation is the recommended optimum biomass CHP technology that provide maximum gross profit with minimal regret/loss of opportunity.

3.2 Sensitivity Analysis of Feed-in Tariff (FiT) Rate on Selection of Optimum Biomass CHP Design

The optimum design recommended by the developed model through MRC approach at different FiT rates are shown in Table 3.4 below using similar case study assumptions in Section 2.3. Lowest maximum regret value, potential minimum and maximum gross profit values between different biomass CHP designs are included to show their changes with FiT rates.

Table 3.4. Optimum Design of Biomass CHP Plant at Different FiT Rates

FiT Rates (%)	Optimum Design	Minimax Regret Value (RM/yr)	Potential Minimum Gross Profit (RM/yr)	Potential Maximum Gross Profit (RM/yr)
-50	Biogas GE	96,457.00	1,007,540.00	1,103,997.00
-30	Syngas + Biogas GE	3,137,180.00	2,392,820.00	5,811,957.00
-10	Syngas + Biogas GE	5,567,543.00	3,778,100.00	10,562,280.00
0	Boiler Steam Turbine	6,684,120.58	4,470,740.00	12,938,480.00
10	Boiler Steam Turbine	6,684,120.58	5,163,380.00	15,314,680.00
30	Boiler Steam Turbine	6,684,120.58	6,548,660.00	20,067,090.00
50	Boiler Steam Turbine	6,684,120.58	7,933,940.00	24,819,490.00

As the FiT rates decreases, the optimum design of biomass CHP plant changed into combined syngas and biogas with gas engine (GE) as power generation technology. At 50% reduction of FiT rates, the optimum design of biomass CHP plant is small capacity biogas generation. The lowest maximum regret value reduces significantly as FiT rates decreases. Although the magnitude of regret value reduces, the potential minimum and maximum gross profit reduces significantly as well. Lower profit margin as FiT rate reduces causes smaller scale biomass CHP design such as biogas and syngas generation with GE more economical compared to boiler with steam turbine. As FiT rate increases, the selection of optimum design for biomass CHP plant remain the same as boiler with steam turbine. Increasing FiT rates will not change the selection on boiler with steam but will significantly increase potential gross profits. This is due to higher revenue on feeding in power to grid thus giving a higher potential of profit as FiT rate increases.

In summary, the impact of FiT rate on selection of biomass CHP design based on Table 3.4 is summarised as following:

1. Decrease in FiT rates will economically favour smaller scale biomass CHP design such as biogas and syngas generation with GE due to lower profit margin.
2. Decrease in FiT rates reduces lowest maximum regret significantly; however, potential profit from biomass CHP plant decreases significantly as well.
3. Higher revenue is generated on feeding in power to grid with higher plant power capacity and FiT rate which eventually provide higher gross profit. Hence, increase in FiT rates will favour larger scale biomass CHP design such as boilers with steam turbine which is able to provide higher power capacity.

3.3 Analysis of Optimum Biomass CHP Design

Table 3.5 below shows the optimum biomass CHP technology that provide maximum gross profit at different power demand with their respective usage of biomass using the developed model. The amount of biomass available was taken as the same as case study as described in Section 2.2.

Table 3.5. Optimum Biomass CHP Design at Different power Demand of Case Study

Power Demand (kW)	POME Consumption (m^3/day)	Usage of Solid Feed (kg/hr)	Optimum Biomass CHP Design
250	0.58	0.00	Biogas with GE
500	1.16	0.00	
750	1.75	0.00	
1000	2.33	0.00	
3000	6.98	0.00	
4000	9.31	0.00	
5000	10.00	1691.00	(Syngas + Biogas) with GE
6000	0.00	7472.37	Boiler with Steam Turbine
7000	0.00	8479.30	
8000	0.00	9486.24	
9000	1.14	10000.00	Combined Boiler with Steam Turbine and Biogas with GE
10000	3.47	10000.00	
13000	9.55	10000.00	

As shown in Table 3.5, biogas with GE engine is used for lower power demand from 250 to 4000 kW where only POME is utilised. This shows that biogas generation through anaerobic digestion of POME is preferred at lower power demand rather than utilising solid biomass such as empty fruit bunches (EFB), palm kernel shell (PKS) and palm mesocarp fibre (PMF). This occurs because utilisation of solid biomass requires pre-treatment equipment such as dryers and shredder, which requires more capital cost. Since the objective function in model focuses on maximising profit and minimising capital costs, the model favours a cheaper route, which is anaerobic digestion equipment. Meanwhile, when the power demand reaches 5000 kW, available POME supply of 10 m^3/day is completely consumed, leaving the remaining amount of power required to be met by syngas generation. Syngas generation was selected to top up remaining power required rather than utilising boiler technology at low usage of solid feed for power generation. This occurs as boilers are more economically viable at larger capacities and high usage of solid feed while syngas is more viable at lower capacities. However, as the power demand increases to range of 6000 to 8000 kW, only solid biomass is utilised through boiler with steam turbine technology without utilising any POME for biogas generation. This shows that boiler steam generation is a favoured selection of CHP technology at higher power demand comparing to syngas and biogas generation. This is because solid biomass that used in boiler can generate higher amount of energy to satisfy higher range of power demand at 6000 to 8000kW. Alternatively, biogas and syngas can be generated to meet this demand. However, due to the high power demand, high amount of biogas and syngas would be required. This will cause the equipment to increase in size much more than of boilers as both biogas and syngas are in gaseous state. Hence, biogas and syngas generation is not economically viable at higher capacity. As the solid biomass are completely utilised as shown in power demand above 9000 kW, POME is utilised to make up to the power demand required which there are not much selection for the model to utilise both biomass. The data stops at power demand of 13000 kW due to insufficient amount of biomass to produce the required power demand. In addition, only GE is selected as power generation technology for biogas and syngas shows that it is a much better selection than micro-turbine and gas turbine. This is due to GE is a widely used and developed power generation technology compare to micro-turbine. Gas turbine is commonly used in natural gas CHP plants but it is only economically viable at very high power demand due to its large power capacity. Therefore, GE is a more economical option than micro-turbine and gas turbine for biomass CHP plant as shown in Table 3.5.

Results from Table 3.5 also indicate other important analysis. It is found that there are common equipment selected for a range of power demands. These equipment are considered as the "must-haves", as without them, the design would be incapable of meeting the required power demands. On top of this, there are certain equipment in the CHP design that appear as "optional". "Optional" equipment are equipment that can be invested in if process designers are ambitious to meet higher power demands. On the other hand, equipment that are never selected throughout the power demand range appear as a "must-avoid". To allow designers to analyse these options, Figure 3.1 summarises the "must-have", "optional" and "must-avoid" equipment in the case study.

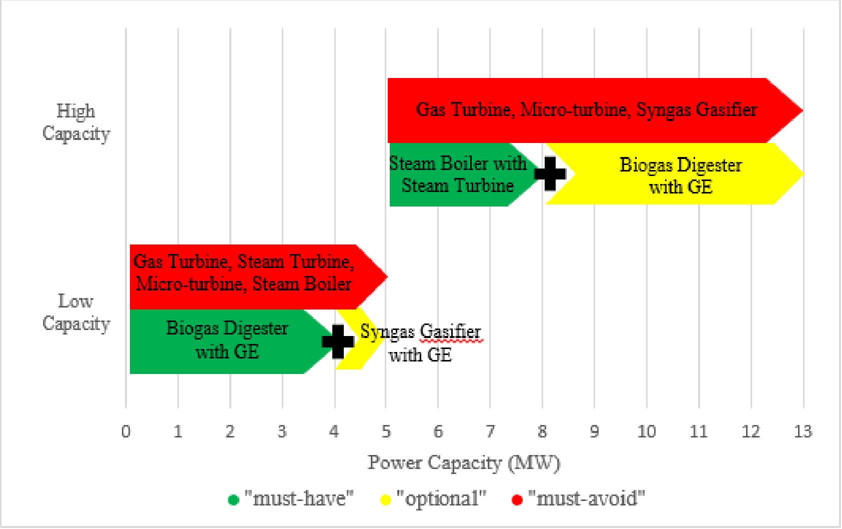

Fig 3.1. "Must-have", "optional" and "must-avoid" Design

For low capacity biomass CHP plant ranges up to 5 MW, the "must-have" design for the CHP plant is biogas generation with GE as shown in Figure 3.1. If the designer would like to invest for a higher power demand at this range, the designer could combine "optional" syngas generation on top of biogas generation to meet higher power demand of 5 MW. For higher capacity biomass CHP plant that ranges from 5 to 13 MW, the "must-have" design for the CHP plant is boiler with steam turbine. Similarly, a higher power demand of 8 to 13 MW could be achieved by combining "optional" biogas with GE on top of boiler with steam turbine. The "must-avoid" design of biomass CHP plant are gas turbine and micro-turbine as these design are not economically viable compare to GE as described.

In a nutshell, Table 3.5 and Figure 3.1 shows a trend of biomass CHP technology selection as below:

1. Biogas generation utilising POME is selected for low power generation.
2. Combined syngas and biogas generation is selected at full usage of POME with low usage of solid biomass at mid power generation.
3. Steam generation using boiler is utilised for high power generation.

4. Internal combustion engine (GE) is used for both syngas and biogas combustion rather than micro-turbine and gas turbine.
5. The “must-have” design for low capacity biomass CHP design ranges up to 5 MW is biogas generation with GE. “Optional” syngas generation design can be invested and combined to achieve a higher power demand from 4 to 5 MW.
6. The “must-have” design for high capacity biomass CHP design ranges from 5 to 13 MW is boiler steam generation with steam turbine. “Optional” biogas generation design can be invested and combined to achieve a higher power demand from 8 to 13 MW.

4 Conclusion

This research work had presented a linear programming systematic framework to design biomass CHP system based on potential loss of profitable opportunity due to varying energy demand. Then, Minimax Regret Criterion (MRC) approach was used to assess potential economic risk of the given biomass CHP design based on energy demand. Based on MRC approach for the case study, the recommended optimum biomass CHP design is steam generation through boiler with steam turbine generating power. This design is selected as the optimum design due to its lowest maximum regret. This means that boiler with steam turbine biomass CHP design will provide minimum potential loss of profitable opportunity across the power demand range of 3000 to 10000 kW. Sensitivity analysis of FiT rates on the selection of biomass CHP design was conducted. Boilers with steam turbine is generally favoured as the FiT rates increases based on the sensitivity analysis of FiT rates at ±10, ±30 and ±50% from its original tariff. This is due to higher revenue is generated on feeding in power to grid with higher plant power capacity and FiT rate which eventually provide higher gross profit. On the other hand, decrease in FiT rates will economically favour smaller scale biomass CHP design such as biogas and syngas generation with GE due to lower profit margin. Besides, design analysis on the trend of the optimum design selected by model was conducted. Biogas with GE utilising POME is favoured for lower power capacity ranges from 250 to 5000 kW. Boilers with steam turbine is favoured for high power capacity ranges from 5000 to 13000 kW instead. Certain equipment will be essential for certain power demand range as described as a “must-have” design. These equipment had been outlined to ease the decision in final selection of process designer. In overall, a systematic framework to design biomass CHP system had been established to recommend an optimum biomass CHP design which minimise the potential loss of profitable opportunity while maximising gross profit. The case study had shown that the framework was able to provide a preliminary design. The model also highlights optional design that allow process designer to invest in to achieve higher power capacity. It is worth mentioning that the mathematical model can be easily revised and reformulated to take in account of other aspects such as variation in biomass supply, variation in tariff rates, and changes in government schemes which will be considered as prospects of future work.

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