Techno-Economic of 100 kW Power Plant from Microwave-Assisted Biodiesel Pyrolysis

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Abstract- Every 1 kg of palm oil fruit produces an empty fruit bunch (EFB) weighing approximately 0.25 kg. The EFB is considered as the agricultural waste of the palm oil industry due to the excessive amounts produced. The majority of EFB is not appropriately utilized and produces a high level of CO_2 as a result of abandonment to landfills. This study investigates the utilization of conventional fast pyrolysis (CFP) to make the biofuel products from EFB waste. Additionally, microwave-assisted pyrolysis (MAP), a new high-performance technique, is also investigated. The calculation of mass and energy balance is conducted using commercial simulation software. The benefits of this plant are investigated in terms of economics and climate change. The results show that neither CFP nor MAP benefits the economy of developing the power plants since they are not profitable. The net present value (NPV) of CFP and MAP are -1,127,674 and -1,073,772 USD, respectively. However, from the climate change aspects, both power plants provide good environmental impact performance. The CO_2 emissions resulting from the non-managed disposal of EFB for the CFP and MAP plants were 924, 917, 895 tCO_2/yr., respectively. Although the development of these plants might not be beneficial from an economic perspective, they contribute significantly to the reduction of CO_2 emissions compared with direct disposal through landfills. This work describes the advantages of using renewable technology in a transparent environmentally friendly process.

Keywords Empty fruit bunch, Fast pyrolysis, Microwave-assisted pyrolysis, Renewable technology, Techno-economics

1. Introduction

According to an international report on palm oil production, Thailand is ranked third in the world for palm oil production, generating 1.8 million tons of palm oil in 2015. Palm oil has become one of Thailand's best-selling products. However, the supply and demand for palm oil can change over time, resulting in shortages during some seasons and oversupply in others. To address the oversupply situation, the Electricity Generating Authority of Thailand (EGAT) subsidizes surplus palm production by purchasing it as fuel for steam boilers, but this process is still not sufficiently effective. Empty fruit bunch (EFB) provides high ash content resulting from direct combustion, thereby impacting on the level of waste disposal at the landfill site. Moreover, the majority of EFB generated during the harvesting season of palm oil fruit is typically disposed directly into open landfills. This EFB residue can potentially emit methane, as a greenhouse gas emission, into the atmosphere, thereby causing climate change [1, 2]. Hence, the utilization of this empty fruit bunch in an appropriate way will mitigate the environmental impact. Basically, energy crops has been used for biofuel production over the last years [3, 4]. The Thai government has launched the project to utilize fast pyrolysis as waste-to-energy technology to transform this agricultural waste into a value-added product. The products obtained from fast pyrolysis mainly comprises biochar, pyrolytic gas, and bio-oil. The project focuses on bio-oil as the main product of this process to finally produce electricity since the benefits of fast pyrolysis contribute to the highest percentage of bio-oil. This technology is also used by power plants to generate electricity [5]. The microwave-assisted pyrolysis (MAP) technique, a novel technology, has recently been studied and received considerable attention from researchers due to its advantage over the conventional pyrolysis method. In practice, implementing the microwave-assisted pyrolysis process requires individual operating conditions, mostly based on the characteristic properties of the biomass. However, the bio-oil produced from the pyrolysis will still be of lower quality compared to petroleum fuel. The heating value of the pyrolyzed bio-oil is basically half as much as the fuel utilized in the power plant. Moreover, the biodiesel should provide the benefit point of green fuel as it not contains sulphur [6]. Hydrotreatment is one of the most common routes for upgrading this bio-oil. It utilizes hydrogen gas to remove sulphur and oxygen as a compound for creating bio-oil with low energy density [7]. The mass and energy balance throughout the process is performed using the Aspen Plus software. Therefore, the objective of this study is to comprehensively determine the economic viability and environmental impact of this biodiesel power plant to conclude whether or not it is a suitable technology for solving the environmental problem. This study analyses both the economic and environmental impact of applying microwave-assisted technology to conventional fast pyrolysis. The main contribution of this paper is stated below:

a) This research focuses on developing biodiesel power plants, specifically in Thailand. Generally, EFB is dumped into landfills or directly thrown into combustion, which is not an environmental-friendly method. This research selects the pyrolysis process as suitable technology for converting the waste into a valuable product (e.g., bio-oil).

b) Conventional fast pyrolysis (CFP) and the novel microwave-assisted pyrolysis (MAP) techniques are compared in terms of energy consumption and environmental impact.

c) A comprehensive investigation was undertaken on the development of the new power plant using these technologies as described in b). The potential impact of this plant covers both the profitability aspect and environmental impact. Hence, this work deals with research on sustainable technology.

2. Methodology

2.1. Raw material (EFB)

The chemical properties of EFB are utilized from the researchers' investigation of EFB [8]. Details of the EFB composition are shown in Table 1.

Table 1. Composition of an oil palm empty fruit bunch in Thailand [8].

Elemental composition	Air-dried basis (% wt.)
Carbon	43.8
Hydrogen	6.20
Oxygen	42.64
Nitrogen	0.44
Sulfur	0.09
Proximate composition	
Moisture	8.34
Volatile	73.16
Ash	6.30
Fixed carbon	12.20

2.2. Process

To achieve efficient utilization of the EFB fast pyrolysis process, the pretreatment must involve making the physical condition of the EFB more compatible with the performance of fast pyrolysis.

2.2.1 Drying and crushing section (A100)

The operating principle of the drying unit is to remove the moisture content contained within the EFB to reduce the heat load caused by moisture evaporation. The designated moisture content of a dried EFB is around 10% due to the wide-ranging conditions performed in many commercial experiments [9]. The low-moisture EFB is then transported to the size reduction unit to diminish the size of the EFB to an appropriate operating condition for the designed pyrolysis process. Abdullah et al. investigated the effect of distribution size on pyrolytic yield, suggesting that between 255–355 μm is preferred for pyrolysis combustion to contribute to lower ash content and fewer blockages in the feeding system [10]. Bridgwater reported that the range of suitable EFB particle sizes should be 250–355 μm, although particles of up to 500 μm were acceptable [11]. Hence, in this study, the researchers have chosen approximately 400 μm as being the most appropriate size for EFB feedstock.

2.2.2 Pyrolysis section (A200)

Fast pyrolysis is a key step in the initial process of converting biomass material into a useful essence. Fast pyrolysis involves the thermal decomposition of carbonaceous organic matter in the absence of oxygen, characterized by temperature and short vapor residence times. Abdullah et al. and Peryoga et al. performed an experimental investigation on the fast pyrolysis condition that contributes to the highest bio-oil yield of EFB. The results indicate a similar condition of pyrolysis, in which the residence time is set around 1.0 s, at a pyrolysis temperature of approximately 500 °C [12, 13]. According to the experimental findings, these conditions provide the highest bio-oil yield of around 50%. To develop this key process at the power plant under study, the fast pyrolysis and kinetic reactions to the EFB decomposition into the pyrolytic product are referred to in the work of Peters et al. [14].

Unlike conventional electrical heating, whereby the heat is transferred from high-temperature gas to the centre of fuel particle through the convection and conduction mechanism, the microwave heating method can penetrate the feedstock particle, and microwave energy is transformed into heat inside the particle.

According to Parvez et al. [15], who studied the development of microwave-assisted pyrolysis on the Aspen Plus software, a complete built-in model is not available in the software to simulate the new pyrolysis mechanism. The development method involves specifying the yield distribution based on the experimental findings of the corresponding system. While Mohd & Afiqah [16] studied the effect of the heat process and temperature on the yield and characteristics of char, bio-oil, and syngas derived from both CFP and MAP of EFB. A comparison study was also performed between the CFP and MAP. This work, therefore, utilized the previously mentioned experimental findings to implement the Aspen Plus model, especially the composition of pyrolytic bio-oil.

2.2.3 Product separation section (A300)

Quick and effective separation of char is essential because it acts as a vapor cracking catalyst and contributes to the formation of polycyclic aromatic hydrocarbons (PAHs) in pyrolysis processes, particularly at low temperatures. A stream containing several components is partially vaporized in a flash drum at a specific pressure and temperature. The first flash drum operated at a temperature of 100 °C and pressure of 1.01325 bars, while the second flash drum operated at 50 °C in vacuum conditions.

2.2.4 Combustion section (A400)

Various research works utilized syngas and biochar to provide heat recovery within a power plant. One example of the heat recovery system in a fast pyrolysis plant is the research work performed by Shemfe et al. [17]. They conducted a techno-economic analysis of biofuel production via fast biomass pyrolysis and subsequent bio-oil upgrading. This section utilizes two RGIBBS reactors to achieve the actual combustion model. The first reactor performs decomposition of the by-product into a constituent compound before feeding into another RGIBBS reactor to complete the combustion mechanism. In order to prevent the ash completely melting, the combustion temperature is 1296 ˚C.

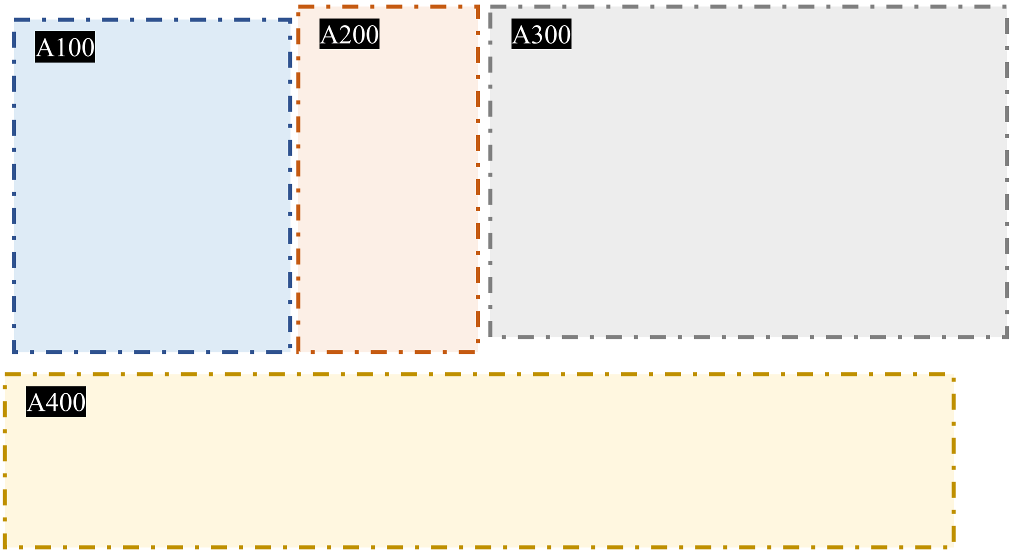

Fig 1. Pretreatment section (A100), Pyrolysis section (A200), Product separation section (A300), Combustion section (A400) in Aspen Plus

2.2.5 Hydrotreatment section (A500)

The thermal instability and low energy density are due mainly to the presence of high oxygen content in the form of water [18]. Hence, an upgrading process is needed. Hydrotreating with hydrogen (H_2) gas is used in this study. Details of the kinetic reaction in the hydrotreatment process are based on the previous study [19]. The hydrogen gas is operated at 90 bars and then mixed with the bio-oil, pumped up to the corresponding pressure. The mixture is then heated to 383 ˚C and sent to the hydrotreater (HDT) to achieve the reaction. The required hydrogen consumption in this study is assumed to be 0.05 g H_2 /g bio-oil [20].

2.2.6 Distillation section (A600)

Subsequently, the bio-oil undergoes hydrotreatment and is distilled to separate the biodiesel from the mixed hydrotreated product that also comprises other types of fractional bio-oil. The distillation process was performed at 20 bars to remove the hydrogen and light hydrocarbon from the hydrotreated stream. Secondly, it is transferred to an adiabatic decanter at 20 bars to remove additional polar compounds from the oil-product. The distillation columns, ultimately producing gasoline and heavy compounds as by-products, then obtain the biodiesel. The RadFrac model represents the distillation columns. The gasoline column consists of nine stages with the partial condenser and column pressure at 1.5 bars. In comparison, the diesel column involves eight stages with the total condenser and column pressure at 0.01 bar.

2.2.7 Hydrocracking section (A700)

Hydrocracking is commonly applied to upgrade the heavier fractions obtained from the distillation of crude oils, including residue. The process adds hydrogen gas to remove impurities such as sulfur to produce a product that meets environmental specifications while converting the heavy feed to the desired boiling range. The heavy compound (represented by chrysene) is cracked into smaller hydrocarbons (C1–C18 hydrocarbons). The main operating condition for the hydrocracking reaction is set at 677 °C and 90 bars. The hydrocracker in this study is modeled using the RStoic reactor, which contains eight reactions, obtained from the work of Sadhukhan et al. [21].

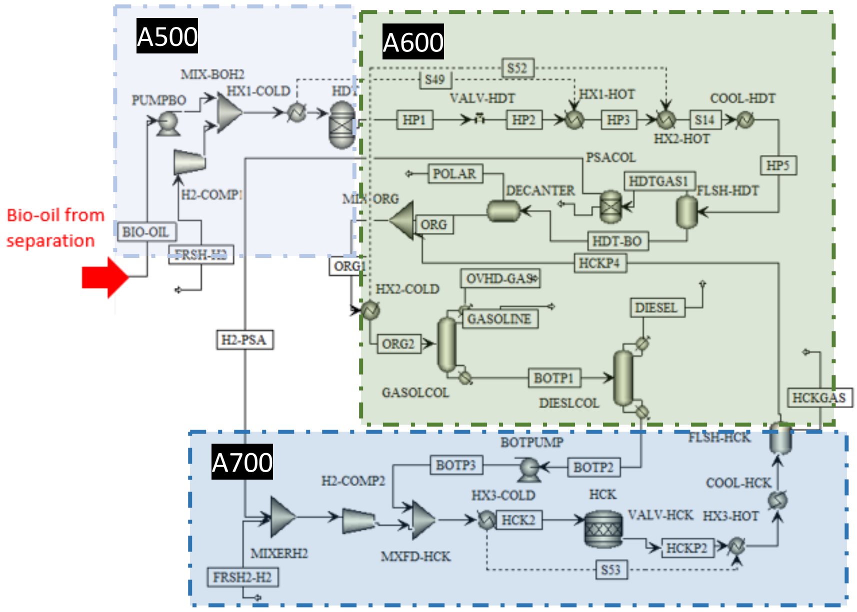

Fig 2. Hydrotreatment section (A500), Distillation section (A600), and Hydrocracking section (A700) in Aspen Plus

2.2.8 Diesel generator

Since no built-in model or function has been created in the Aspen Plus software, it might be developed in the other simulated model platform. It is assumed that the development of the diesel engine model is due to the calculation simplicity of the energy balance in the system. Nevertheless, since there is no open-source mathematical model for Genset, a mathematical diesel engine is developed instead, and the energy equation utilized following Vatakit [22]. To completely calculate the work output of the Genset system, the efficiency of mechanical-to-electrical power conversion is assumed to be 95% [23]. Due to their capability for calculating the diesel engine energy balance, some Genset machines are representative of the geometry found in engine specifications. Table 2 shows the diesel generator for specifications at 100 kW.

Table 2. Specifications of a 100-kW diesel engine

Specifications	Units	Values
Rated speed	RPM	1,800
Peak power at max. rated speed	kW	100
Engine displacement	Liter	5.9
Fuel consumption rate	Liter/hr	30.7

2.3. Economic Evaluation

NPV (net present value), which is one of the key costing analysis metrics, has been used for assessment of renewable technology [24]. In this study, NPV will be represebt forprofitability indicator.The discount rate reflects the opportunity cost of the capital mobilized, which increases with the estimated danger involved in developing a new project, and inflation rate [25, 26].

Costs in this work mainly comprise Fixed Capital Investment (FCI) and operating costs; the former basically consisting of two components: the cost of equipment purchased, and procurement and construction cost. In the case of equipment purchased, this study utilizes the Aspen Process Economic Analyzer (APEA) V8.8 to evaluate the price of the engineering device. However, the results for the evaluated price of the equipment from APEA V8.8 reveal that the price was determined on the 2014 basis. Hence, it needed to be upgraded to the present value for the 2019 fiscal year. The Chemical Engineering Plant Cost Index (CEPCI) was selected for this purpose. For the procurement and construction phase, this study evaluated the considered items of FCI following the Plant Design and Economics for Chemical Engineers (International Edition) [27]. However, to accurately evaluate the FCI cost, it should be specifically determined based on a particular area. Therefore, this study mainly utilizes information from the research of Delivand et al. [28] and other relevant work, with the average values presented in Table 3. The biodiesel power plant is located in Surat Thani Province, which has the highest palm oil fruit production [29].

Table 3. Evaluation of each capital item

Capital- items	Percentage cost of equipment purchased
Site preparation costs	3.78
Civil work	14.19
Piping	3.43
Installation cost	17.67
Instrumentation and control costs	15.46
Electricity transmission	11.54
Auxiliary costs	6.17
Indirect costs (engineering work)	7.59
Contingency	7.1
Total	86.93

In the case of operating costs, this study used numerous documents to fulfil all the required operating parameters. All of these documents are from national report, the researches of public companies, and other relevant literatures. A summary of the operating cost items is presented in Table 4.

Table 4. Operating cost items and cost estimation

Item	Value
Raw material	0.017 USD/kg
Hydrogen gas	5.03 USD/kg
Labor cost	• Specialized engineering: one position—13,548 USD/yr. • Technical staff: four positions—18,580 USD/yr. • Maintenance engineering: one position—7,742 USD/yr. • Secretary: one position—11,612 USD/period
Operation and maintenance (O&M) costs	3% of fixed capital investment
Utilities	• Electricity 0.11 USD/kWh • Cooling water 0.032 USD/m^3 • Waste disposal 11.34 USD/ton
Plant overhead	5% of fixed capital investment

However, since prices in any market can change
However, since prices in any market can change annually, some cost changes are considered. Labor operating costs will be increased by approximately 2.7% [30]. In the case of O&M, the expenditure cost will be increased annually by 5% [31]. Moreover, the other parameters were assumed to increase annually by 4%, according to the predicted inflation rate [32]. This plant was assumed to operate for a total of 6,000 hrs.

From the income perspective, two profitable products are generated at this biodiesel power plant: gasoline and electricity. The gasoline price was approximately 0.74 USD/liter in March 2020. The electricity price is calculated in the form of FiT (feed-in-tariffs). The FiT rate comprises three parts: Fixed FiT_f, Variable FiT_v, and premium FiT. The total electricity sales price is shown in equation (1). In the case that the biodiesel power plant capacity in this work is below 1 MW, then the rate of FiT_F, $FiT_{v,2017}$, $FiT_{premium}$ would be 0.1, 0.072, and 0.016 USD per kWh, respectively. Moreover, the FiTv,2017 rate will be increased by 1.5% every year due to the rise in the core inflation rate creating greater market competition [33].

$$FiT_F + FiT_{v,2017} + FiT_{premium} = FiT_{Total}\ \text{(sales price)} \qquad (1)$$

2.4. Environmental impact

In the traditional management of EFB waste, field abandonment is harmful to the environment. Hence, the global warming potential of this field abandonment by the EFB should be quantitatively evaluated. According to the measurement of gases emitted from direct disposal of the EFB [34], due to field abandonment, the total global warming gas discharged was 1.54 kgCO_2 eq./kg EFB.

The Life-Cycle Assessment (LCA) environmental methodology was applied in this work. The LCA approach focuses on the potential global warming category of the boundary system at this biodiesel power plant, which is gate-to-gate [35]. All the relevant information was compiled to determine the environmental impact, and the chemical composition performance of the exhaust stream, as well as energy consumption throughout the plant. Energy usage can be considered as one of the main contributory factors in global warming since the majority of electricity produced by power plants also emits greenhouse gases into the atmosphere. Consequently, this biodiesel power plant, by consuming energy, indirectly emits CO_2 to the environment. This CO_2 emission is sometimes called "carbon intensity" and is expressed as a fraction of the CO_2 emission weight required to generate electricity in kWh units. The energy consumed by this biodiesel power plant for its operating function was equivalent to 0.34 kgCO_2/kWh, according to a national report [36], subsequently interpreted into GWP in terms of CO_2 equivalent.

Regarding the diesel engine [37], de Almeida et al. studied the engine performance and CO_2 emissions of small-scale stationary diesel engines utilizing 100% of biodiesel derived from EFB. These researchers conducted an experimental investigation on the emissions of a diesel generator. The summary results indicated that the CO_2 emissions equated to approximately 8.3% wt. of the total exhaust gases from the combustion engine at full load. This percentage emission was utilized to determine the CO_2 emissions in this study.

3. Results and Discussions

3.1. Pyrolysis yield distribution

According to the results of the simulation, the CFP process provided a yield distribution for biochar, bio-oil, and pyrolytic gas of 14, 58, and 28% wt., respectively. The prior experimental results for the fast pyrolysis of EFB was maximized at around 55% wt. [5]. It can be observed that the bio-oil yield in the simulation is somewhat higher than that obtained in the experimental study. This might be due to the separation process since a single condenser tube was used in the experiments to condensate the pyrolytic vapor. Whereas, this study employed two flash drums as a distillate vessel, which is the same equipment used in the actual industry since it provides high performance in separation [38]. This concept is also supported by the main influential factor, namely, rapid cooling in the condensation process [39]. Since the actual process might not fully represent the simulated operation, the calculated results may deviate slightly.

In the case of pyrolyzed yield distribution for MAP, the simulated results indicate biochar, bio-oil, and pyrolytic gas yields of 11, 62, and 26% wt., respectively. Considering the bio-oil yield obtained from MAP, Salema & Ani [40] conducted experimental microwave pyrolysis on EFB. They found that the microwave-assisted pyrolyzed bio-oil yield, without the addition of activated carbon, was approximately 10% wt. This yield was apparently lower than that obtained from conventional pyrolysis. These researchers mentioned that this was because more rapid heating contributed to plasma development. Consequently, this plasma formation could entirely pyrolyze the EFB pellet into char due to the extreme temperature. However, according to a review of microwave-assisted conversion of biomass [41], the plasma formation could initiate gasification, and enhance the syngas yield. Moreover, Salema & Ani further stated that the plasma was not found in the MAP by adding the activated carbon as a microwave absorber. This is somewhat contrary to the report by Horikoshi et al., who conducted an experimental study on a generation of hot-spots (so-called “micro-plasma”) by microwave heating. They found that plasma formation is mostly located in activated carbon [42]. Moreover, Arshad et al. [43] reported that the parameter playing the most important role in efficiently controlling the hot-spot formation is the design of the microwave cavity. Nevertheless, not only can the rapid heating phenomenon affect product yield, but many other significant parameters may also influence it. For instance, sample weight, the characteristic properties of biomass, particle size, reaction power, reaction time, and reactor design [44]. Furthermore, even though various parameters can cause divergent results, their measurement accuracy is also challenged [45]. An example of such measurement limitation is the utilization of thermocouples inside a microwave field. This can cause incorrect temperature recording and may damage the thermocouple in severe cases of hot-spot formation, ultimately resulting in research difficulties [43]. Finally, according to the theoretical principles of the MAP process, when used on lignocellulosic biomass, it shows a positive trend, producing both a higher yield and better quality of bio-oil [46, 47]. However, it is difficult to precisely predict the bio-oil yield for MAP simply by judging any single factor, because MAP biomass is significantly dependent on many components, as mentioned above. The research results in previous literature are sometimes inconsistent due to a lack of understanding concerning in-depth theoretical MAP mechanisms [48], and further study is still required.

Hence, if an optimum, complete MAP process can be successfully developed, it might provide a higher bio-oil yield from lignocellulosic biomass.

However, comparison of thermal efficiency between the CFP and MAP shows that the latter is 3.3% more efficient. This might be due to the generation of cyclohexane resulting from MAP implementation. This compound is considered to be a high-value hydrocarbon, satisfying the standard for transportation fuel. This result is similar to that presented in some of the relevant literature. For example, Parvez et al. [15] reported that the implementation of MAP provides 13.5% greater thermal efficiency than CFP. Therefore, it can be concluded that MAP contributes to lower energy consumption compared to CFP.

3.2. Economic evaluation

Figure 3 shows the influential factors in the cost of electricity production. It can be observed that plant overheads and labor operating costs are ranked top of all the investment costs. This is similar to a relevant previous study on a micro-scale biomass power plant [49]. Since plant overheads strongly depend on the number of processes and this plant has been upgraded, the overheads are substantially higher. As for the labor operating costs, since this is a very small-scale plant, the economies of scale are not achieved. The maintenance cost is the next highest after labor. It is noticeable that all the main cost influencers are operating parameters. Hence, the investment costs at this plant can be minimized by optimizing these factors. The cost breakdown for the MAP plant is presented in Fig 4. The items in the MAP production costs do not significantly diverge from the breakdown costs for CFP. The largest difference between these two plants is the hydrogen cost. Since the MAP plant produces higher bio-oil yield, it also requires more H_2 gas to interact with the faster feeding rate involved in the hydrotreatment process. The total capital costs of the CFP and MAP plants are 1,208,981 and 1,228,815 USD, respectively. As for the profitability of this project, the NPV value of CFP and MAP are -1,127,674 and -1,073,772 USD, respectively. These two plant types are considered as unsatisfactory projects from the economic perspective. This is not surprised in the case of very-small scale of biomass-derived electricity. Normally, the biomass energy production be backed up by the government, the private sector, non-governmental organizations, etc [50].

Fig 1. *Share of production cost items for the CFP plant*

Fig 2. Share of production cost items for the MAP plant

3.3. Environmental impact

To investigate the merits of developing a biomass-fired power plant, three disposal methods for EFB are compared in terms of environmental impact. Figure 5 demonstrates that the conventional renewable power plant produced lower CO_2 emissions of around 8 tCO_2/yr., compared with the non-managed disposal of EFB. The MAP gave a better climate change performance by providing lower CO_2 emissions of 22 tCO_2/yr., compared to the conventional plant (CFP). The EFB-fired power plant has many engineering processes that require plenty of energy, and it produces flue gases as a result of the chemical and combustion processes involved in generating electricity. A simple review of this notion might depict a major climate change contributor. However, an in-depth examination of the biomass-fired power plant, using competent methodology and software, would reveal the benefits of renewable technology.

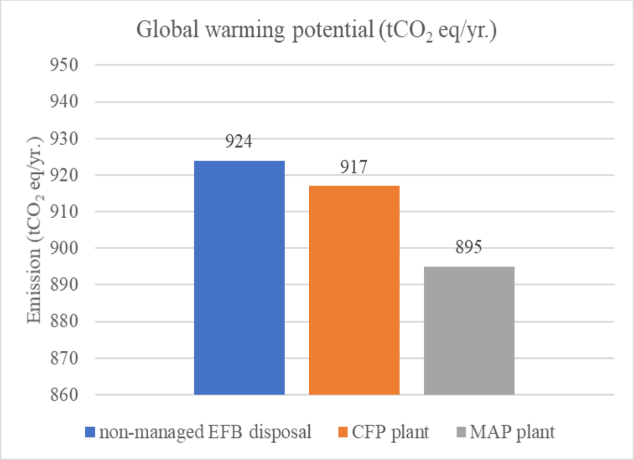

Fig 5. Climate change comparison between the power plants and direct disposal

4. Conclusion

This work focuses on the suitable utilization of EFB waste that traditionally produces high CO_2 emissions, as reported in several research works. Conventional Fast Pyrolysis (CFP) is used to transform EFB into biofuel. This biofuel can then be fed into a diesel generator to provide electricity. Additionally, microwave-assisted pyrolysis (MAP) is also investigated in this study since it has the advantage of producing a higher pyrolysis performance compared to CFP. This study utilizes the Aspen Plus V8.8 to model the pyrolysis plants and calculate the mass and energy balance throughout the plants. To research the suitability of the developed plants, economic and environmental impacts were considered and evaluated. The results from the economic perspective show that both CFP and MAP plants are not considered suitable for initiation since they are not profitable. The net present value (NPV) is used as the profitability indicator, with the NPV for the CFP and MAP being -1,127,674 and -1,073,772 USD, respectively. However, from the environmental impact perspective, both CFP and MAP gave a better climate change performance compared to the non-managed disposal of EFB. CO_2 emissions from the disposal of EFB, CFP, and MAP plants were 924, 917, 895 tCO_2/yr., respectively. Current environmental issues, including climate change, are receiving considerable interest across the world. Even though the economic aspect might not be satisfied, the environment, which is directly related to the quality of life, is of profound importance and a topic of concern for many people.

Acknowledgements

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References

[1] K. Saswattecha, M. Cuevas Romero, L. Hein, W. Jawjit, and C. Kroeze, "Non-CO$_2$ greenhouse gas emissions from palm oil production in Thailand." Journal of Integrative Environmental Sciences, 12(sup1): pp. 67–85, 2015.

[2] F. Sulaiman and N. Abdullah, "Optimum conditions for maximising pyrolysis liquids of oil palm empty fruit bunches." Energy, 36(5): pp. 2352–2359, 2011.

[3] M. A. Sanz-Bobi, F. De Cuadra, & C. Batlle, "A review of key points of an industrial biogas plant. A European perspective." International Conference on Renewable Energy Research and Applications (ICRERA) (pp. 1-6). IEEE, November 2012.

[4] Y. Ulusoy, A. H. Ulukardesler, R. Arslan, & Y. Tekin, "Energy and emission benefits of chicken manure biogas production—A case study." In 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA) (pp. 648-652). IEEE, November 2017.

[5] D. Chiaramonti, A. Oasmaa, and Y. Solantausta, "Power generation using fast pyrolysis liquids from biomass. Renewable and Sustainable Energy Reviews", 11(6): pp. 1056–1086, 2007

[6] A. S. A. A. Elgharbawy, "cost analysis for biodiesel production from waste cooking oil plant in Egypt." International Journal of Smart Grid-ijSmartGrid, 1(1), pp. 16-25, 2017

[7] H. Wang, J. Male, Y. Wang, "Recent advances in hydrotreating of pyrolysis bio-oil and its oxygen-containing model compounds." Acs Catalysis. May 3;3(5):1047-70, 2013.

[8] S. Kerdsuwan, and K. Laohalidanond, "Renewable energy from palm oil empty fruit bunch." Renewable energy-trends and applications, pp. 123–150, 2011.

[9] N. Abdullah, and F. Sulaiman, "The properties of the washed empty fruit bunches of oil palm." Journal of Physical Science, 24(2): pp. 117, 2013.

[10] N. Abdullah, H. Gerhauser, and A. Bridgwater, "Bio-oil from fast pyrolysis of oil palm empty fruit bunches." Journal of Physical Science, 1(1): pp. 57–74, 2007.

[11] A. V. Bridgwater, "Review of fast pyrolysis of biomass and product upgrading." Biomass and bioenergy, 38: pp. 68–94, 2012.

[12] N. Abdullah, H. Gerhauser, and F. Sulaiman, "Fast pyrolysis of empty fruit bunches." Fuel, 89(8): pp. 2166–2169, 2010.

[13] Y. Peryoga, M. D. Solikhah, and A. A. Raksodewanto, "Production cost assessment of palm empty fruit bunch conversion to bio-oil via fast pyrolysis." Int. J. Adv. Sci. Eng. Inf. Technol, 4(6): pp. 394–400, 2014.

[14] J. F. Peters, S. W. Banks, A. V. Bridgwater, and J. Dufour, "A kinetic reaction model for biomass pyrolysis processes in Aspen Plus." Applied Energy, 188: pp. 595–603. 2017.

[15] A. M. Parvez, T. Wu, M. T. Afzal, S. Mareta, T. He, and M. Zhai, "Conventional and microwave-assisted pyrolysis of gumwood: A comparison study using thermodynamic evaluation and hydrogen production." Fuel Processing Technology, 184: pp. 1–11, 2019.

[16] B. Mohd, and N. Afiqah, "Conventional and microwave pyrolysis of empty fruit bunch and rice husk pellets." University of Sheffield, 2017.

[17] M. Shemfe, S. Gu, and B. Fidalgo, "Techno-economic analysis of biofuel production via bio-oil zeolite upgrading: An evaluation of two catalyst regeneration systems." Biomass and Bioenergy, 98: pp. 182–193, 2017.

[18] Y. Luo, V. K. Guda, P. H. Steele, and G. Wan, "Hydrodeoxygenation of oxidized and hydrotreated bio-oils to hydrocarbons in fixed-bed continuous reactor." BioResources, 11(2): pp. 4415–4431, 2016.

[19] Y.-H.E. Sheu, R. G. Anthony, and E. J. Soltes, "Kinetic studies of upgrading pine pyrolytic oil by hydrotreatment." Fuel processing technology, 19(1): pp. 31–50, 1988.

[20] K. Iisa, R. J. French, K. A. Orton, A. Dutta, and J. Schaidle, "A.Production of low-oxygen bio-oil via ex situ catalytic fast pyrolysis and hydrotreating." Fuel, 207: pp. 413–422, 2017.

[21] J. Sadhukhan, and K. S. Ng, "Economic and European union environmental sustainability criteria assessment of bio-oil-based biofuel systems: refinery integration cases." Industrial & Engineering Chemistry Research, 50(11): pp. 6794–6808, 2011.

[22] K. Vatakit, "A Study of Boost Pressure on Efficiency of an Agricultural Single Cylinder Diesel Engine – Theory and Calculations.," in 13th Thai Society of Agricultural Engineering. 2016: The Imperial Mae Ping Hotel, Chiang Mai.

[23] L. R. Radovic, and H. H. Schobert, "Energy and Fuels in Society: Analysis of Bills and Media Reports." McGraw-Hill., 1997.

[24] K. E. Okedu, & M. Al-Hashmi, "Assessment of the cost of various renewable energy systems to provide power for a small community: Case of Bukha, Oman." *International Journal of Smart Grid*, *2*(3), 172-182, 2018.

[25] O. Žižlavský, "Net present value approach: method for economic assessment of innovation projects. Procedia-Social and Behavioral Sciences" 156(26): pp. 506–512 2014.

[26] Y. Qiu, C. Yuan, X. Tang, J. Tang, Y. Zhang, & X. Bai, "Techno-economic assessment of a PV/SC hybrid Power System Integrated into 2240 PCTC Ro-Ro Ship." In 2019 8th International Conference on Renewable Energy Research and Applications (ICRERA) (pp. 75-80). IEEE, (2019, November).

[27] M. S. Peters, and K. D. Timmerhaus, "Plant design and economics for chemical engineers." 1980.

[28] M. K. Delivand, M. Barz, S. H. Gheewala, and B. Sajjakulnukit, "Economic feasibility assessment of rice straw utilization for electricity generating through combustion in Thailand." Applied Energy, 88(11): pp. 3651–3658, 2011.

[29] Department of Alternative Energy Development and Efficiency, T.D.E.D.E. Potential of palm oil biomass. 2016; Available from: http://webkc.dede.go.th/testmax/node/2529, (Last accessed on January, 2019).

[30] C. Aemkulwat, "Labor force structure change and Thai labor market, 1990–2008." in Paper Second ANDA International Seminar on Skills Development for the Emerging New Dynamism in Asian Developing Countries under Globalization, Phnom Phen. 2010.

[31] S. Udomsri, A. R. Martin, and T. H. Fransson, "Economic assessment and energy model scenarios of municipal solid waste incineration and gas turbine hybrid dual-fueled cycles in Thailand." Waste Management, 30(7): pp. 1414–1422, 2010.

[32] T. Nyoni, "Understanding inflation patterns in Thailand: An ARMA approach.", 2019.

[33] Energy, M.o. Alternative Energy Development Plan. 2015; Available from: http://www.dede.go.th/download/files/AEDP2015_Final_version.pdf. (Accessed: November 2019).

[34] H. Fujita, K. Nakano, T. Chaisomphob, and E. Hambali, "Greenhouse Gas Emission of Electricity Generation and Field Abandonment Scenarios Using Empty Fruit Bunches at a Palm Oil Mill, Surat Thani Province, Thailand." Journal of the Japan Institute of Energy, 98(5): pp. 119–123, 2019.

[35] L. Jacquemin, P. -Y. Pontalier, and C. Sablayrolles, "Life cycle assessment (LCA) applied to the process industry: a review." The International Journal of Life Cycle Assessment, 17(8): p. 1028–1041, 2012.

[36] (EPPO), E.P.a.P.O., Thailand Power Development Plan (PDP, 2018). 2018, Ministry of Energy: Energy Policy and Planning Office (EPPO). p. 105.

[37] S. C. De Almeida, C. R. Belchior, M. V. Nascimento, L. d. S. Vieira, and G. Fleury, "Performance of a diesel generator fuelled with palm oil." Fuel, 81(16): pp. 2097-2102, 2012.

[38] Chemtech, S., Gas/liquid separation technology. 2010.

[39] C. C. Poh, N. A. Hassan, N. A. A. Raman, N. A. M. Shukry, M. N. M. Warid, M.K. I. M. Satar, C. R. Ismail, S. A. Hassan, and N. Mashros, "Effect of fast pyrolysis bio-oil from palm oil empty fruit bunch on bitumen properties." in IOP Conference Series: Materials Science and Engineering. 2018. IOP Publishing.

[40] A. A. Salema, and F. N. Ani, "Pyrolysis of oil palm empty fruit bunch biomass pellets using multimode microwave irradiation." Bioresource technology, 125: pp. 102–107, 2012.

[41] A. M. Bundhoo, "Microwave-assisted conversion of biomass and waste materials to biofuels." Renewable and Sustainable Energy Reviews, 82: pp. 1149–1177, 2018.

[42] S. Horikoshi, A. Osawa, M. Abe, & N. Serpone, "On the generation of hot-spots by microwave electric and magnetic fields and their impact on a microwave-assisted heterogeneous reaction in the presence of metallic Pd nanoparticles on an activated carbon support." The Journal of Physical Chemistry C, 115(46), 23030-23035, 2011.

[43] H. Arshad, S. A. Sulaiman, Z. Hussain, Y. Naz, and F. Basrawi, "Microwave assisted pyrolysis of plastic waste for production of fuels: a review." in MATEC Web of Conferences. EDP Sciences, 2017.

[44] Y.- F. Huang, P. -T. Chiueh, and S.-L. Lo, "A review on microwave pyrolysis of lignocellulosic biomass." Sustainable Environment Research, 26(3): pp. 103–109, 2016.

[45] D. V. Suriapparao, and R. Vinu, "Bio-oil production via catalytic microwave pyrolysis of model municipal solid waste component mixtures." RSC Advances, 5(71): pp. 57619–57631, 2015.

[46] A. Al Shra'ah and R. Helleur, "Microwave pyrolysis of cellulose at low temperature. Journal of analytical and applied pyrolysis" 105: pp. 91–99, 2015.

[47] S. Farag, D. Fu, P. G. Jessop, and J. Chaouki, "Detailed compositional analysis and structural investigation of a bio-oil from microwave pyrolysis of kraft lignin." Journal of Analytical and Applied Pyrolysis, 109: pp. 249–257, 2014.

[48] Y. Zhang, P. Chen, S. Liu, P. Peng, M. Min, Y. Cheng, E. Anderson, N. Zhou, L. Fan, and C. Liu, "Effects of feedstock characteristics on microwave-assisted pyrolysis–a review. Bioresource technology", 230: pp. 143–151, 2017.

[49] N. Abdoulmoumine, A. Kulkarni, S. Adhikari, S. Taylor, and E. Loewenstein, "Economic analysis of municipal power generation from gasification of urban green wastes: case study of F ultondale, A labama, USA." Biofuels, Bioproducts and Biorefining, 6(5): pp. 521–533. H. Poor, An Introduction to Signal Detection and Estimation, New York: Springer-Verlag, 1985, ch. 4. (Book Chapter), 2012.

[50] W. Phoochinda, "Sustainability approach for energy production using biomass at household and community levels: A case study in Thailand." International Journal of Renewable Energy Research (IJRER), 5(3), 859-872, 2015.