**Case study: Preliminary assessment of integrated palm biomass biorefinery for
bioethanol production utilizing non-food sugars from oil palm frond petiole**

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Abstract

In this case study, a preliminary assessment on the bioethanol production from oil palm frond (OPF) petiole sugars within an integrated palm biomass biorefinery was carried out. Based on the case study of 4 neighbouring palm oil mills, approximately 55,600 t/y of fermentable sugars could be obtained from OPF petiole. The integrated biorefinery will be located at one of the 4 mills. The mill has potential excess energy comprising 3.64 GWh/y of electricity and 177,000 t/y of steam which are sufficient to run the biorefinery. With 33.9 million litres/y of bioethanol production, the specific production cost of bioethanol is estimated at \$ 0.52/l bioethanol, compared to \$ 0.31–0.34/l bioethanol produced from sugarcane and \$ 0.49–0.60/l bioethanol from other lignocellulosics. The net energy ratio of 7.48 for bioethanol production from OPF provides a promising alternative for OPF utilization as a non-food sugar feedstock.

Keywords: bioethanol, biofuel, biorefinery, non-food fermentable sugar, oil palm frond petiole, oil palm biomass

1. Introduction

Oil palm frond (OPF) is the most abundant oil palm biomass produced at oil palm plantations compared to other biomass. It was reported that over 50 million tonnes of OPF was generated annually in Malaysia [1], which are available throughout the year as the fronds are regularly cut during the harvesting of fresh fruit bunches (FFB). The OPF consists of the petiole which is the basal part of the branch and many long leaflets on either side of the branch. The top two-thirds of the frond which is the leafy part contain 66% of the nutrients, while the petiole is rich in cellulosic materials and sugars at 60% and 66%, respectively [2,3]. The nitrogen

content is high in the leafy part as compared to the petiole [4], suggesting the suitability of the leafy part as a natural fertiliser for the oil palm, whereas the petiole part can be exploited for the production of biofuels and biobased chemicals [2]. A previous report illustrated the economic viability of renewable sugars from OPF as fermentation feedstock for the production of the bioplastic poly(3-hydroxybutyrate), (P(3HB)) within an integrated palm biomass biorefinery [5]. Meanwhile, OPF juice was proven as an alternative fermentation substrate for the production of bioethanol [6,7]. In another research, a process optimization of an ultrasonic-assisted organosolv/liquid oxidative pretreatment (SOP) of OPF was able to recover cellulose, bioethanol and biochemicals (i.e. phenolic compounds) simultaneously in a biorefinery concept [8]. However, the main obstacles for exploiting the OPF are logistics i.e. collection and transportation of the biomass out of the plantations.

Therefore, this paper proposes a mechanism for utilizing the OPF in an efficient manner. The OPF petiole can be easily collected and transported together with the harvested FFB and transported to the nearest palm oil processing mill. Only the petiole part of the OPF will be collected as it contains more fermentable sugars compared to the leafy part. About half of the fresh OPF petiole (by weight) can be converted to OPF juice by simple pressing, thus providing a big potential as fermentation medium. The juice was found to be rich in sugars at 78.42 g/l, with 73% glucose, 25% sucrose and 2% fructose [3]. On the other hand, the OPF pressed fibre gave about 95% of holocellulose conversion by wet disc-milling and enzymatic hydrolysis, thus suggesting OPF pressed fiber as a new promising fermentation feedstock [7]. The sugars produced from OPF petiole at the mills will be concentrated and transported to an integrated biorefinery for conversion into bioethanol via fermentation. The bioethanol is finally recovered through distillation process. All the processing steps will utilize the excess steam and energy at the mills.

In this paper, a mechanism for fermentable sugars and bioethanol production from OPF petiole is proposed via an integrated technology approach to an existing palm oil mill in order to utilize the surplus energy available at the palm oil mill. Currently, most palm oil mills are self sufficient in terms of energy without relying on external energy for operation. The normal practice is by deploying a cogeneration approach to produce steam and electricity for the milling process [9]. Typical palm oil mills utilize readily available biomass after the oil extraction from the FFB as boiler fuel which comprise of mesocarp fibre and shell. The steam produced at the mill is normally more than sufficient for the required use and thus the excess steam is released to the atmosphere. As reported by Chiew et al. [10], 23.8 MJ of electricity and 24.2 MJ of steam remain unused in the process or released to the air after meeting the electricity and steam demands of the mill. Currently, palm oil mill managers do not put any attention on this issue as the water and biomass fuel can be obtained at no charge. Hence, this study was aimed to assess the feasibility of integrating a bioethanol production plant from OPF petiole to an existing palm oil mill to utilize excess steam and electricity. The energy balance at the existing mill and energy required for fermentable sugars and bioethanol production from OPF were estimated. The process and cost models of bioethanol production from OPF sugars were developed using SuperPro Designer software version 8.0 by Intelligen Inc., Scotch Plains, New Jersey, USA.

2. Methods

2.1. Basis of the proposed model

In this study, it is assumed that OPF petiole sugars produced from at least 4 palm oil mills will be transported to a biorefinery for bioethanol production within an 80 km radius. In the business model proposed, the sugar production plant and the biorefinery for bioethanol production are considered as separate entities. The sugar production plant is done at the individual mills and hence generate profit from the sale of OPF sugars to the biorefinery. Additionally, it is assumed that the biorefinery will be located at one of the 4 mills to utilize the surplus energy from the palm oil mill. It is estimated that external energy will be required by the biorefinery if OPF petiole sugars are supplied from more than 4 palm oil mills. The average processing capacity of oil palm FFB is 240,000 t/y/mill [11] with average OPF petiole collected at 57,600 t/y/mill. The schematic diagram of the proposed concept is shown in Fig. 1. The main criteria to be considered in choosing the ideal palm oil mill to locate the biorefinery is the sufficient excess energy available at the palm oil processing lines to run the biorefinery. As an example, palm oil mill no. 4 was chosen to locate the biorefinery.

Figure 1. Schematic diagram of a proposed integrated palm biomass biorefinery concept for bioethanol production from OPF petiole.

2.2. Process description

2.2.1. Fermentable sugars production from OPF petiole

The fermentable sugars production is carried out by the oil palm processing mills and supplied to the biorefinery. The processing steps were discussed by Zahari et al. [5]. The fresh OPF petiole are pressed to obtain the free sugars in the juice and additional sugars are obtained from the treatment and saccharification of the OPF petiole pressed fibre residue. The sugars are then partially concentrated by evaporation and transported to a centralized biorefinery to be used as a fermentation feedstock for bioethanol production.

2.2.2 Bioethanol production from fermentable sugars

A block flow diagram with the major processing steps and products of the biorefinery are shown in Fig. 2. The baseline scenario considers the design of a biorefinery with a capacity to process 55,600 tonnes of sugars produced from 230,400 tonnes of OPF petiole per year from 4 neighbouring palm oil mills. The fermentable sugars from the storage tank at the neighbouring palm oil mills are transported to the biorefinery for bioethanol production.

The concentrated sugar solution is sterilized prior to fermentation by an HTST-type treatment (high temperature short time). In this treatment, the pressure of the concentrated juice is increased to 0.6 MPa, with the mixture heated to 121°C for 30 minutes before being cooled to 31.9°C [12]. This step is recommended due to the benefits of fermentable sugars preservation and thermal inactivation of bacterial contaminants. Since the major sugars present in the OPF are glucose and xylose, the usage of suitable recombinant strain of *S. cerevisiae* that can convert both sugars to bioethanol simultaneously would be more economically feasible. The engineered *S. cerevisiae* industrial yeast strain WXY12 was reported to have the highest bioethanol production when fermenting a mixture of glucose and xylose at a yield of 0.48g/g total sugars [13]. These results collectively suggest that yeast WXY12 may be a suitable engineered strain for further study into large-scale bioethanol production from mixed sugars present in lignocellulosic hydrolysates. The fermentation is carried out in batch process at 30°C for 24 hours.

Figure 2. Block flow diagram of bioethanol production from OPF sugars at the biorefinery.

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157

158 Fermentation liquor containing bioethanol is centrifuged prior to the distillation process to

159 remove the water. Fermented liquor is heated to a suitable temperature before entering the

first distillation column. Hydrous bioethanol obtained from the stripping and rectification stages is dehydrated in order to remove the remaining moisture and produce anhydrous bioethanol. Dehydration with molecular sieves is used to considerably reduce the steam requirement for this step.

2.3. Process design description of bioethanol production from OPF sugars

A process concept was developed based on the current state-of-the-art bioethanol production technology. Input data and data on operating conditions of the examined process were obtained from literature, while equipment and process data were obtained from Vulcurovic et al. [14] and directly from the SuperPro Designer software version 8.0. The design basis is 197 tonnes of OPF sugars per batch with the maximum number of batches per year predicted by the model. A simplified process flow diagram (PFD) is shown in Fig. 3. The entire process includes the fermentation section and downstream processing section.

In developing the fermentation process, urea was used as nitrogen source. Initial inoculum concentration was set at 10% of biomass quantity in relation to the amount of cultivation media. Fermentation was conducted in eight 385,000 litres (16.5m height and 5.5m diameter) vessels. Fermentation broth was sent to a disc-stack centrifuge in order to remove most of the biomass. After centrifugation the liquid fraction was sent to a distillation column with a height of 13.2 m and diameter 5.3 m, that operates in a mode to remove the CO₂ and as little bioethanol as possible overhead, while removing about 95% of water to the bottom. The bioethanol mixture with water is removed as a vapour side draw from the column

Figure 3. Simplified process flow diagram of bioethanol production from fermentable sugars of OPF.

and fed directly to the rectification column which recovers 76.9% of bioethanol. Overhead vapour from the rectification column is fed to the molecular sieve adsorption unit to produce 98.94% pure bioethanol. The non-fermentable material from the centrifugation unit is dried to produce wet distiller's grains, which contains about 45% solids. In addition, water removed from the distillation and stripping unit are recovered as process water and can be recycled.

The design basis is 33.9 million litres of 98.94% pure ethanol per year, which is produced from 55,600 tonnes of OPF sugars.

2.4. Bioethanol production cost

Economic analysis was performed on the proposed process model and is given as an executive summary of project indices. As a basis for calculation, the data for cost estimation was taken from bioethanol produced from sugar beet juice as a reference [14]. The utilities supply was obtained from the excess electricity, water and steam available at the existing palm oil mill. In the biorefinery concept, the plant is proposed to be constructed next to a palm oil mill where the excess steam and electricity from the mill can be tapped and connected to the bioethanol production plant. The fixed capital cost consists of equipment cost for the bioethanol production plant including costs for installation, piping and instrumentation.

The project life was fixed at 25 years, with 10% linear full depreciation of the process equipments for 10 years period. Labour cost was estimated based on 21 number of workers as per current salary rate set by the Public Service Department or *Suruhanjaya Perkhidmatan*

Awam Malaysia [15]. As a basis for calculation, the exemption of energy and utility costs which includes electricity and water were calculated based on current industrial tariff set by *Tenaga Nasional Berhad* (the national energy company) and *Syarikat Air Negeri Sembilan* (the state water supply company). The repair and maintenance costs were assumed at 4% of fixed capital investment. The price of fermentable sugars paid to the 4 palm oil mills was estimated at \$ 0.25/kg sugar, higher than that reported by Zahari et al. [5] at \$ 0.20/kg sugar in order to support the neighbouring mills. The yeast and urea were used at 5 g/l and 2.3 g/l at a price of \$ 0.26/kg and \$ 0.39/kg, respectively [16].

2.5. *Process analysis*

A model was developed to estimate the material flow in the fermentable sugars and bioethanol production. The energy requirements for processing the OPF petioles and bioethanol production were then estimated based on values reported in published literature. The energy resources including electricity, steam, water and fermentable sugars obtained from OPF petioles for bioethanol production were based on the data listed in Table 1.

2.5.1 *Energy cogeneration and utilization at palm oil processing mill*

The process flow diagram of fermentable sugars production from OPF at an integrated biorefinery attached to a palm oil mill is illustrated in Fig. 4. The process starts from the oil palm plantation where the harvested FFB and OPF petioles are collected together and transported to the palm oil mill. The FFB is fed into the palm oil processing line starting from sterilization until CPO production. The steam required for FFB processing is supplied by the cogeneration system at the palm oil mill which comprise of boiler, turbine and back pressure

236 receiver. Biomass fibre and shell obtained after oil extraction is returned to the boiler as
237 biofuel. Approximately 15% w/w of FFB processed ends up as mesocarp fibre and 8% as
238 palm kernel shell after the oil pressing, all of which are fed into the boiler. It is estimated that
239 for the annual mill capacity of 240,000 t/y of FFB processing, a total of 55,200 tonnes of
240 mesocarp fibre and shell (0.66:0.34) are burned in the boiler. With calorific values of 19,068
241 and 20,108 kJ/kg, in mesocarp fibre and palm kernel shell, respectively [10], 299,325 tonnes
242 of high pressure steam at 20 bars can be produced based on boiler efficiency of 77.4% [9].
243 This amount of steam would generate 7.72 GWh of electricity assuming the turbine has
244 similar efficiency as boiler. Considering that 17 kWh [17] is required to process each tonne of
245 FFB, approximately 4.08 GWh/y of electricity would be required. This shows that the excess
246 and available power of 3.64 GWh/y could be tapped to run the proposed sugar recovery
247 machines as well as the bioethanol production plant. On the other hand, approximately 510
248 kg steam at a lower pressure of 3 bars from the back pressure receiver (BPR) is required to
249 process each tonne of FFB [18]. Overall, 176,925 tonnes of excess steam would be available
250 each year at every mill. This source of energy could also be utilized to run the fermentable
251 sugars production from OPF, sugar storage as well as bioethanol recovery.

252 **Table 1.** Assumptions for sugars and bioethanol production from OPF petiole at integrated biorefinery**.

Description	Value	Reference
Average capacity of individual mill	2.4x10 ⁸ kg/y of FFB processed	[11]
Average weight of FFB	25 kg/FFB	[19]
Hence, amount of FFB processed	9.6x10 ⁶ FFB/y	
Average weight of OPF petiole	3 kg/OPF petiole	The oil palm tree ages from 8 - 20 years. Calculation was made based on the current practice at the plantation for every 1 FFB harvested, 2 OPF will be pruned.
Total weight of OPF petiole generated	57,600 t/y	
Amount of juice obtained (50% w/w)	28,800 t/y	
Upon concentrating (50% water removal)	14,400 t/y concentrated juice	
Amount of OPF petiole fibre obtained (50% w/w)	containing 160 g/l sugars 28,800 t/y	
Amount of glucose extracted from OPF fibre		
Amount of xylose extracted from OPF fibre	7,186 t/y 4,566 t/y	80% hollocellulose with 95% conversion containing 46.9% and 29.8%, glucose and xylose, respectively [4]
Power demand for OPF preparation and juice extraction	16 kWh/t OPF	[20]
Power demand for sugars recovery from OPF pressed fibre (mechanical equipments)	24 kWh/t wet OPF pressed fibre	[21]
Electricity for mechanical vapor recompression (MVR) evaporator	43.4 kWh/t dried OPF pressed	[20,22]

Steam demand for OPF juice evaporation	fibre	
Steam demand for evaporation of sugar	86.6 kg/t OPF	Estimation based on 3 multiple effects evaporator
hydrolysate from OPF pressed fibre	18.7 kg/t dried OPF pressed fibre	Four effects of mechanical vapor recompression (MVR)
Steam demand for sterilization of sugar		evaporator [23]
syrup	563 kg/t sugar	Temperature at 121°C
Steam demand for distillation and		
dehydration of hydrous bioethanol	2.55 kg/l bioethanol	[20]
Power demand for bioethanol production		
	12 kWh/t sugar	[21]
Water usage		
	0.0106 m ³ /l bioethanol	[24]

253 *Evaporation of 50%, w/w of water from OPF juice and sugar hydrolysate, respectively at each palm oil mill

254 **Energy demand was estimated based on sugarcane processing.

2.5.2 *Energy usage for sugars production from OPF petiole*

The energy usage in the sugars production line is summarized in Fig. 4. The steam requirements for juice extraction and sugars recovery from OPF was estimated based on sugarcane juice as baseline (Table 1). Concentration of the juice by evaporator requires only 5,000 tonnes of steam per year to remove 50% water from OPF juice and produce 14,400 t/y sugar syrup using three effects evaporation system. The concentrated OPF juice will have a sugar concentration of approximately 160 g/l. On the other hand, the sugar remaining in the OPF pressed fibre is extracted by wet disc milling followed by enzymatic saccharification. Based on optimum solid loading rate of 15%, w/w, approximately 6.7 litres of citrate buffer (0.05M, pH 4.8) is required for each kilogram of dried OPF pressed fibre in the saccharification process, thus further evaporation is needed to remove half of the water in the sugar hydrolysate. Only 380 tonnes of steam is required to concentrate the sugar hydrolysate to 174 g/l by using four effects mechanical vapour recompression (MVR) evaporators. Both sugars from OPF juice and OPF pressed fibre are combined to produce final sugar concentration of approximately 170 g/l sugar slurry and stored at 50°C before being transported to the biorefinery for bioethanol production. In addition, the final sugar slurry exiting the final evaporator has a temperature of around 50°C. Therefore, minimum steam would be required annually to maintain this mild temperature storage, which could be obtained from the exhausted vapour from the evaporators. In total, about 5,400 tonnes of steam will be utilized for sugar recovery from OPF petiole at the biorefinery.

On the other hand, 0.92 GWh/y of electricity is required for OPF preparation and juice extraction, 0.69 GWh/y for processing of OPF pressed fibre (drying and saccharification) and 0.87 GWh/y for running the MVR evaporators.

2.5.3 *Energy utilization at bioethanol production line*

The estimated excess steam available after the sugar recovery from OPF is 171,600 t/y which will be utilized for sterilization of fermentation medium and the bioethanol distillation and dehydration process. Approximately 31,300 t/y steam is required for the sterilization process and 86,000 t/y steam is required to distillate and dehydrate the anhydrous bioethanol. On the other hand, the electricity consumption for bioethanol production is estimated at 0.67 GWh/y with assumption of 12 kWh/t of lignocellulosic material [20,22]. After considering all the energy and power requirements, there is still excess energy available i.e. 54,400 t/y steam and 0.49 GWh/y electricity. Therefore, the current energy available at palm oil mills is assumed to be sufficient for running bioethanol production from OPF sugars.

2.6 *Energy efficiency analysis of bioethanol from OPF*

The energy efficiency analysis was based on an indicator used for evaluating biofuels production, called "Net Energy Ratio (NER)".

$$\text{Net Energy Ratio} = \frac{\text{Energy output}}{\text{Energy input}}$$

Equation 1

When the energy ratio is greater than one, the process is energetically feasible and possibly leads to a reduction in greenhouse gas emissions. Energy input was calculated as the sum of the primary energy input including diesel, electricity and steam for fermentable sugars and bioethanol production. The output energy was estimated based on the energy in the

bioethanol produced from the OPF. The lower heat of combustion of bioethanol is 21.2 MJ/l [25].

3 Results and discussion

3.1 Materials flow of fermentable sugars production and bioethanol production from OPF petiole at biorefinery

This study proposed only one biorefinery for bioethanol production, whereby the fermentable sugars from OPF is obtained from 4 neighbouring palm oil mills. The capacity of OPF petiole processed at one palm oil mill for fermentable sugars production is estimated at 57,600 t/y.

This capacity is more than that reported by Zahari et al. [7], as the data in this study was based on the higher OPF petiole average weight of 3 kg obtained from the oil palm trees aging from 8 to 20 years old. Annually, it is estimated that 25 million tonnes of fresh OPF petioles can be collected from all plantations in Malaysia. The materials process flow at the biorefinery is shown in Fig. 5, summarizing the estimated annual production capacity of fermentable sugars as well as the bioethanol produced from the OPF petiole sugars.

Upon concentration of the OPF juice to remove 50% water content, the capacity of concentrated OPF juice obtained from one mill is 14,400 tonnes. With specific gravity of the concentrated juice at 1100 kg/m³, the volume of the concentrated OPF juice obtained is estimated at 13.1 million litres containing approximately 160 g/l sugars. Hence, 2,100 tonnes of sugars can be obtained from the OPF juice at each palm oil mill. On the other hand, OPF fibre was found to contain 80.58% holocellulose based on the fibre weight. The extraction of sugars from dried OPF pressed fibre was carried out by wet disc milling followed by

337 enzymatic saccharification to obtain glucose and xylose. Based on Roslan [4], maximum
338 glucose and xylose concentrations of 0.469 g and 0.298 g, respectively per g of OPF petiole
339 could be obtained from the saccharification method, with 95% of holocellulose being
340 converted into mixed sugars. Therefore, after removing 30% remaining moisture in the OPF
341 pressed fibre, the potential glucose and xylose obtained would be 7,200 tonnes and 4,600
342 tonnes, respectively. The mixed slurry of sugars from OPF juice and OPF pressed fibre
343 hydrolysate will be combined in a storage tank at the individual palm oil mills (170 g/l) prior
344 to transporting to the biorefinery. Overall, the total sugars potentially collected at the
345 biorefinery is estimated to be 55,600 tonnes annually. These sugars are renewable
346 fermentation feedstock for bioethanol production. From this amount of sugars, approximately
347 33.9 million litres per year of bioethanol could be produced assuming that 94% of the
348 theoretical yield can be achieved by the engineered yeast strain [13].

349 **Figure 5.** Overall mass balance for the production of bioethanol from OPF petiole at the biorefinery.

3.2 Economic analysis of bioethanol from OPF petiole

The results of the economic analysis are shown in Table 2. The total capital investment cost for this production plant is obtained by adding together the values of the direct fixed capital (DFC), working capital and start-up and validation costs. DFC represents the sum of the total plant cost (TPC) and costs for contractor's fees and contingency (CFC). Furthermore, the TPC consists of the total plant direct cost (TPDC) and the total plant indirect cost (TPIC). While the TPIC depends on the costs for engineering and construction, the TPDC expenses include the costs for equipment purchase, installation, process piping, instrumentation, insulation electrical, building, yard improvement and auxiliary facilities. The purchasing cost for major equipment items listed in Table 2 is based on offers from the suppliers of equipment or taken from the report of Aden et al. (2002).

Table 2. Economic analysis of the proposed model for bioethanol production from OPF sugars.

Capital investment cost (\$)	69,259,000
Direct fixed capital DFC = TPC + CFC (\$)	61,609,000
Total plant cost TPC = TPDC + TPIC (\$)	53,573,000
Total plant direct cost TPDC (\$)	35,715,000
Equipment purchase cost (\$)	11,649,000
Fermentors (\$)	4,000,000
Disc-stack centrifuge (\$)	2,950,000
Batch distillation vessel (\$)	478,000
Rectification column (\$)	57,000
Molecular sieves (\$)	2,700,000
Stripping unit (\$)	525,000
Heat exchanger (\$)	8,000
Unlisted equipment (\$)	932,000

Installation (\$)	4,495,000
Process piping (\$)	4,077,000
Instrumentation (\$)	4,660,000
Insulation (\$)	349,000
Electrical (\$)	1,165,000
Buildings (\$)	4,660,000
Yard improvement (\$)	1,165,000
Auxiliary facilities (\$)	3,495,000
Total plant indirect cost TPIC (\$)	17,858,000
Engineering (\$)	7,143,000
Construction (\$)	10,715,000
Contractor's fee & contingency CFC (\$)	8,036,000
Contractor's fee (\$)	2,679,000
Contingency (\$)	5,357,000
Working capital (\$)	1,489,000
Startup cost (\$)	6,161,000
Operating cost (\$/year)	16,633,000
Raw materials (\$/year)	15,117,000
Yeast (\$/year)	726,748
OPF sugars (\$/year)	13,888,500
Urea (\$/year)	501,399
Labour (\$/year)	1,220,498
Laboratory/QC/QA (\$/year)	183,000
Utilities (\$/year)	0
Unit production cost (\$/l)	0.52

\$ = US dollar

Base year: 2015

The total annual operating and maintenance cost for the biorefinery is estimated to be \$ 16.63 million. The maintenance cost is estimated at 4% of the total investment cost. Based on the

yield of bioethanol obtained at 48% from the sugars consumed, approximately \$ 13.9 million is spent on the fermentable sugars from OPF supplied by neighbouring mills at a price of \$ 0.25/kg. Even though this mill gate price of OPF sugar is half of the market price, the neighbouring mills producing fermentable sugars from OPF are expected to receive additional profits of \$ 4.4 million per year based on sugar production cost from OPF petioles as reported by Zahari et al. [5]. The operation of bioethanol biorefinery requires manpower of 21 workers comprising of 1 plant manager, 2 engineers, and 18 operators. In addition, 0.67 GWh/y at a price of \$ 0.12/kWh [26] would be utilized for operating the bioethanol plant along with 781,000 m³ of fresh water [24] to run the process at a price of \$ 0.49 per cubic meter of fresh water [27]. Interestingly, the cost of utilities could be waived as the excess steam, electricity and water can be obtained from the palm oil processing mill. This will cut the cost at approximately \$ 1.83 million per year.

The expected revenue from bioethanol is \$ 24.06 million per year, which is calculated from the annual expected bioethanol produced multiplied with the bioethanol price of \$ 0.71 per litre [28]. Moreover, additional revenue can be obtained from the selling of Distillers Dried Grains and Solubles (DDGS) at \$ 655,000 per year. For the case of sugarcane bioethanol, the producer improved the profitability of bioethanol production by selling surplus electricity produced from cogeneration system of sugarcane bagasse and trash which is used as fuels in bioethanol production to obtain steam and electricity [21]. The reduction on bioethanol production costs as low as \$ 0.18/l can be obtained by bioethanol production with electricity co-product credit [24].

The bioethanol production cost from OPF was estimated at \$ 0.52/l, putting the feedstock in the middle position between sugarcane and lignocellulosic bioethanol (Table 3). The

estimated cost in this study is rather accurate due to bioethanol from OPF being considered a combination of first and second generation bioethanol.

Table 3. Production cost of bioethanol from various feedstocks

Types of feedstock	Production scale (litre bioethanol/year)	Cost of production per litre (USD/litre bioethanol)	Net energy ratio (NER)	References
Corn	47,619,048	0.46		[24]
			1.3	[29]
Sugarcane	-	0.34	7.9	[30]
	180,000,000	0.313		[31]
Lignocellulosic	19,047,619	0.60		[24]
Empty fruit bunch (EFB)	36,500,000	0.49		[32]
			2.26	[33]
OPF	33,900,000	0.52	7.48	This study

Since EFB is also an abundant oil palm biomass which can be easily obtained at the palm oil mill after oil extraction, it creates interest as a feedstock for bioethanol production. Quintero et al. [32] reported the bioethanol production cost from EFB at \$ 0.49/l which is comparable to OPF. Production cost for bioethanol in Brazil is the world's lowest with the average cost approximately \$ 0.165 per litre, according to the Brazilian Sugarcane Industry Association. Many factors contribute to the low cost of Brazil's bioethanol which include favourable climate conditions, low labour costs, big scale of operation and mature infrastructure built over at least three decades. Brazilian bioethanol with attached co-generation facilities has been shown to consistently result in a production cost lower than its corresponding petroleum

product, although this depends significantly upon net production costs due to an electricity co-product credit [24].

The economic analysis (Table 4) indicates the positive Net Present Value (NPV) at \$ 29,196,000, whereby this investment expense can be paid back in 8.6 years, which is acceptable and reasonable. The Return of Investment (ROI) is a performance measure used to evaluate the efficiency of an investment. That is, if an investment does not have a positive ROI, then the investment should not be undertaken. This project yields an after-tax IRR of 12.11%, with income taxes set to 40%. Based on these results, with a project lifetime of 25 years and depreciation period of 10 years with a salvage value 5% DFC, this project represents a very attractive investment, i.e. the examined system is economically viable.

Table 4. Project indices of the bioethanol production process model

Project indices	Value
Gross margin (%)	33.93
Return on Investment (%)	11.63
Payback time (years)	8.60
Internal Rate of Return after taxes (%)	12.11
Net Present Value at 7.00% (\$)	29,196,000

3.3 Energy efficiency analysis

The energy input from the plantation includes the energy for cultivating the oil palm tree as well as transportation based on the fuel cost to carry the OPF petioles from the plantation to

the palm oil mill. However, energy for fertilizer at the plantation is estimated to be zero as the fertilizer used is actually for palm oil production. On the other hand, transportation energy of OPF petioles from plantation to the mills was estimated at 5% of current usage whereby an additional cart carrying the OPF petioles was proposed to be attached to the existing truck carrying harvested FFB. In order to transport the fermentable sugars to a central biorefinery for bioethanol production, 0.0125 litre diesel/tonne sugar/km is required [34]. Moreover, at the biorefinery, the processing energy of OPF petioles to obtain sugars and later bioethanol was estimated. A total of 650 MJ per tonne of OPF is required to extract sugars from both OPF juice and OPF pressed fibre until the final product is produced.

It is estimated that 146 litres of bioethanol can be produced from each tonne of OPF.

Therefore, the estimated output energy from 1 tonne OPF is 3100 MJ with the assumption that the lower heat of bioethanol combustion is 21.2 MJ/l [25]. The saccharified OPF residue estimated at 146 kg per tonne of OPF processed will be used as biofuel to feed the existing boiler at 77% efficiency. Therefore, 1,767 MJ of energy can be produced from the residue with the assumption that calorific value of OPF is 15,720 kJ/kg [35]. Hence, the total energy output was estimated to be 4,867 MJ from the sum of the bioethanol and the residue.

Therefore, the net energy ratio for bioethanol production from OPF was estimated to be 7.48, which is comparable to sugarcane and better than corn and EFB (Table 3). All the steam and power demands for bioethanol production is assumed to be sufficiently supplied by the excess energy available at the existing palm oil mill. Therefore, sugars from OPF is a promising non-food feedstock for bioethanol production for better sustainability.

As the world's second largest palm oil producer, Malaysia has the potential to produce second generation bioethanol from the abundant oil palm biomass. Currently, the bulk of oil

palm biomass is left in the field while the rest is mulched or returned to the field as fertilizer. In addition, in a business-as-usual scenario, Malaysia's palm oil industry will utilize 12 million tonnes of biomass per annum for use in wood products and bioenergy by 2020. Moreover, producing bioethanol and biobased chemicals from oil palm biomass will offer increased wealth as well as new and better jobs [2]. In December 2010, Sime Darby Plantation announced its collaboration with Mitsui Engineering and Shipbuilding Co. of Japan to construct and operate a bioethanol demonstration plant which converts EFB into bioethanol. The plant can process 1.25 tonnes of EFB a day using hydrothermal pretreatment and enzymatic hydrolysis technology. It is understood that Sime Darby is still collecting operational data to confirm the technical feasibility for commercial scale production of bioethanol from EFB [36].

However, bioethanol from fresh OPF petiole has better potential compared to EFB in terms of bioethanol production capacity as summarized in Table 5. In general, it was estimated that 3,900 million litres of bioethanol can be obtained from both OPF juice and pressed fibre collected from all the oil palm plantations in Malaysia. This figure is much higher than the expected bioethanol production from EFB.

Table 5. Potential value of sugars and bioethanol from OPF and EFB

	OPF	EFB*	Reference
Sugars production (t/ha/y)	1.18**	0.324 0.594	[19] [37]
Bioethanol production (l/ha/y)	720***	372 487	[38] [32]

*Average weight based on dry basis: 1.55 tonnes of EFB collected per hectare.

** It was estimated that 4.9 tonnes of OPF petiole/ha/y can be obtained. Percentage of sugar yield from OPF was estimated at 24% (w/w)

*** Percentage of bioethanol yield at 48% (weight of bioethanol/weight of sugars)

Total planted area approximately 5.1 million hectares [11]

4 Conclusion

The preliminary assessment on the integration of a biorefinery to an existing palm oil mill shows good potential for scaling up of bioethanol production from OPF as the palm oil mills have excess energy and steam to support the biorefinery. The estimated net energy ratio of 7.48 and production cost of \$ 0.52/l bioethanol offers a good promise for commercialization. Introducing a mandate for bioethanol blending of 10 percent in Malaysia would generate a domestic demand of 1.3 million tonnes of bioethanol per annum [39]. This capacity is possible based on the current capacity of oil palm plantations in Malaysia.

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References

- [1] Ofori-Boateng C, Lee KT. Same-vessel enzymatic saccharification and fermentation of organosolv/H₂O₂ pretreated oil palm (*Elaeis guineensis* Jacq.) fronds for bioethanol production: Optimization of process parameters. *Energy Convers Manag* 2014;78:421–30. doi:10.1016/j.enconman.2013.10.075.
- [2] Malaysia Innovation Agency (MIA). National Biomass Strategy 2020 : New wealth creation for Malaysia's biomass industry 2013. http://innovation.my/pdf/1mbas/Biomass_Strategy2013.pdf (accessed December 10, 2014).
- [3] Zahari MAKM, Zakaria MR, Ariffin H, Mokhtar MN, Salihon J, Shirai Y, et al. Renewable sugars from oil palm frond juice as an alternative novel fermentation feedstock for value-added products. *Bioresour Technol* 2012;110:566–71. doi:10.1016/j.biortech.2012.01.119.
- [4] Roslan AM. Oil palm frond petiole conversion into biosugars and bioethanol. PhD thesis. Kyushu Institute of Technology, Japan, 2014.
- [5] Zahari MAKM, Ariffin H, Mokhtar MN, Salihon J, Shirai Y, Hassan MA. Case study for a palm biomass biorefinery utilizing renewable non-food sugars from oil palm frond for the production of poly(3-hydroxybutyrate) bioplastic. *J Clean Prod* 2015;87:284–90. doi:10.1016/j.jclepro.2014.10.010.
- [6] Abdullah SSS, Shirai Y, Bahrin EK, Hassan MA. Fresh oil palm frond juice as a renewable, non-food, non-cellulosic and complete medium for direct bioethanol production. *Ind Crop Prod* 2015;63:357–61. doi:10.1016/j.indcrop.2014.10.006.
- [7] Zahari MAKM, Abdullah SSS, Roslan AM, Ariffin H, Shirai Y, Hassan MA. Efficient utilization of oil palm frond for bio-based products and biorefinery. *J Clean Prod* 2014;65:252–60. doi:10.1016/j.jclepro.2013.10.007.
- [8] Ofori-Boateng C, Lee KT, Saad B. A biorefinery concept for simultaneous recovery of cellulosic ethanol and phenolic compounds from oil palm fronds: Process optimization. *Energy Convers Manag* 2014;81:192–200.

doi:10.1016/j.enconman.2014.02.030.

- [9] Nasrin AB, Ravi N, Lim WS, Choo YM, Fadzil AM. Assessment of the performance and potential export renewable energy (RE) from typical cogeneration plants used in palm oil mills. *J Eng Appl Sci* 2011;6:433–9.
- [10] Chiew YL, Iwata T, Shimada S. System analysis for effective use of palm oil waste as energy resources. *Biomass and Bioenergy* 2011;35:2925–35. doi:10.1016/j.biombioe.2011.03.027.
- [11] Malaysia Palm Oil Board (MPOB). Number & Capacities of Palm Oil Sectors 2013 n.d. <http://bepi.mpob.gov.my/index.php/statistics/sectoral-status/120-sectoral-status-2013/619-number-a-capacities-of-palm-oil-sectors-2013.html> (accessed April 24, 2014).
- [12] Dias MOS, Ensinas A V., Nebra SA, Maciel Filho R, Rossell CEV, Maciel MRW. Production of bioethanol and other bio-based materials from sugarcane bagasse: Integration to conventional bioethanol production process. *Chem Eng Res Des* 2009;87:1206–16. doi:10.1016/j.cherd.2009.06.020.
- [13] Cao L, Tang X, Zhang X, Zhang J, Tian X, Wang J, et al. Two-stage transcriptional reprogramming in *Saccharomyces cerevisiae* for optimizing ethanol production from xylose. *Metab Eng* 2014;24:150–9. doi:10.1016/j.ymben.2014.05.001.
- [14] Vučurović DG, Dodić SN, Popov SD, Dodić JM, Grahovac J a. Process model and economic analysis of ethanol production from sugar beet raw juice as part of the cleaner production concept. *Bioresour Technol* 2012;104:367–72. doi:10.1016/j.biortech.2011.10.085.
- [15] Suruhanjaya Perkhidmatan Awam Malaysia (SPA) 2014. http://www.spa.gov.my/Portal/Deskripsi_Tugas (accessed August 8, 2014).
- [16] Sánchez-Segado S, Lozano LJ, de Los Ríos AP, Hernández-Fernández FJ, Godínez C, Juan D. Process design and economic analysis of a hypothetical bioethanol production plant using carob pod as feedstock. *Bioresour Technol* 2012;104:324–8. doi:10.1016/j.biortech.2011.10.046.

- [17] Yoshizaki T, Shirai Y, Hassan MA, Baharuddin AS, Raja Abdullah NM, Sulaiman A, et al. Improved economic viability of integrated biogas energy and compost production for sustainable palm oil mill management. *J Clean Prod* 2013;44:1–7. doi:10.1016/j.jclepro.2012.12.007.

- [18] Vijaya S, Ma AN, Choo YM, Nik Meriam NS. Life cycle inventory of the production of crude palm oil - a gate to gate case study of 12 palm oil mills. *J Oil Palm Res* 2008;20:484–94.

- [19] Shamsudin S, Md Shah UK, Zainudin H, Abd-Aziz S, Mustapa Kamal SM, Shirai Y, et al. Effect of steam pretreatment on oil palm empty fruit bunch for the production of sugars. *Biomass and Bioenergy* 2012;36:280–8. doi:10.1016/j.biombioe.2011.10.040.

- [20] Ensinas A V., Nebra SA, Lozano MA, Serra LM. Analysis of process steam demand reduction and electricity generation in sugar and ethanol production from sugarcane. *Energy Convers Manag* 2007;48:2978–87. doi:10.1016/j.enconman.2007.06.038.

- [21] Dias MOS, Junqueira TL, Cavalett O, Pavanello LG, Cunha MP, Jesus CDF, et al. Biorefineries for the production of first and second generation ethanol and electricity from sugarcane. *Appl Energy* 2013;109:72–8. doi:10.1016/j.apenergy.2013.03.081.

- [22] Renó MLG, Olmo OA del, Palacio JCE, Lora EES, Venturini OJ. Sugarcane biorefineries: Case studies applied to the Brazilian sugar–alcohol industry. *Energy Convers Manag* 2014;86:981–91. doi:10.1016/j.enconman.2014.06.031.

- [23] Davis R, Tao L, Tan ECD, Biddy MJ, Beckham GT, Scarlata C, et al. Process design and economics for the conversion of lignocellulosic biomass to hydrocarbons : dilute-acid and enzymatic deconstruction of biomass to sugars and biological conversion of sugars to hydrocarbons. NREL/TP-5100-60223. 2013. doi:10.2172/1107470.

- [24] BBI Biofuels Canada. Biofuel Costs , Technologies and Economics in APEC Economies Final Report. APEC#210-RE-01.21. Singapore: 2010.

- [25] Murata Y, Tanaka R, Fujimoto K, Kosugi A, Arai T, Togawa E, et al. Development of sap compressing systems from oil palm trunk. *Biomass and Bioenergy* 2013;51:8–16.

doi:10.1016/j.biombioe.2012.12.007.

- [26] Tenaga Nasional Berhad (TNB). Pricing & Tariff (200866-W) n.d. <http://www.tnb.com.my/tnb/business/for-industrial/pricing-tariff.html#industrial> (accessed August 6, 2014).
- [27] Kementerian Tenaga, Teknologi Hijau dan Air (KTTHA). Laman Web Rasmi Kementerian Tenaga, Teknologi Hijau dan Air 2014. http://www.kettha.gov.my/portal/index.php?r=kandungan/index&menu1_id=4&menu2_id=67&menu3_id=136#.U-h8L_mSx8k (accessed August 11, 2014).
- [28] Aguilar FX, Cai Z, Mohebalian P, Thompson W. Exploring the Drivers' side of the "Blend Wall": U.S. Consumer Preferences for Ethanol Blend Fuels. *Energy Econ* 2015;49:217–26. doi:10.1016/j.eneco.2015.01.019.
- [29] von Blottnitz H, Curran MA. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *J Clean Prod* 2007;15:607–19. doi:10.1016/j.jclepro.2006.03.002.
- [30] van den Wall Bake JD, Junginger M, Faaij A, Poot T, Walter A. Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and Bioenergy* 2009;33:644–58. doi:10.1016/j.biombioe.2008.10.006.
- [31] Dias MOS, Cunha MP, Jesus CDF, Scandiffio MIG, Rossell CEV, Rubens Maciel Filho, et al. Simulation of ethanol production from sugarcane in Brazil: economic study of an autonomous distillery. 20th Eur. Symp. Comput. Aided Process Eng. – ESCAPE20, 2010, p. 733–8.
- [32] Quintero JA, Moncada J, Cardona CA. Techno-economic analysis of bioethanol production from lignocellulosic residues in Colombia: A process simulation approach. *Bioresour Technol* 2013;139:300–7. doi:10.1016/j.biortech.2013.04.048.
- [33] Tan HT, Lee KT, Mohamed AR. Second-generation bio-ethanol (SGB) from Malaysian palm empty fruit bunch: energy and exergy analyses. *Bioresour Technol* 2010;101:5719–27. doi:10.1016/j.biortech.2010.02.023.

- [34] Ludin NA, Bakri MAM, Kamaruddin N, Sopian K, Deraman MS, Hamid NH, et al. Malaysian oil palm plantation sector: exploiting renewable energy toward sustainability production. *J Clean Prod* 2014;65:9–15. doi:10.1016/j.jclepro.2013.11.063.

- [35] Atnaw SM, Sulaiman SA, Yusup S. Syngas production from downdraft gasification of oil palm fronds. *Energy* 2013;61:491–501. doi:10.1016/j.energy.2013.09.039.

- [36] Choong MY. “Useless” bioethanol now finds wide uses. *Star* , 2 Oct 2012.

- [37] Cui X, Zhao X, Zeng J, Loh SK, Choo YM, Liu D. Robust enzymatic hydrolysis of Formiline-pretreated oil palm empty fruit bunches (EFB) for efficient conversion of polysaccharide to sugars and ethanol. *Bioresour Technol* 2014;166:584–91. doi:10.1016/j.biortech.2014.05.102.

- [38] Tan L, Yu Y, Li X, Zhao J, Qu Y, Choo YM, et al. Pretreatment of empty fruit bunch from oil palm for fuel ethanol production and proposed biorefinery process. *Bioresour Technol* 2013;135:275–82. doi:10.1016/j.biortech.2012.10.134.

- [39] Suruhanjaya Tenaga. Statistics - Malaysia Energy Information Hub n.d. http://meih.st.gov.my/statistics?p_auth=Imi5aPOe&p_p_id=Eng_Statistic_WAR_STOASPublicPortlet&p_p_lifecycle=1&p_p_state=maximized&p_p_mode=view&p_p_col_id=column-1&p_p_col_pos=1&p_p_col_count=2&_Eng_Statistic_WAR_STOASPublicPortlet_execution=e1s1&_Eng_Stat (accessed June 27, 2015).