A Technical and Economic Analysis of Heat and Power Generation from Biomethanation of Palm Oil Mill Effluent

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ABSTRACT

Palm oil mill effluent (POME) has been identified as one of the major sources of aquatic pollution in Malaysia. due to its high strength and economic importance. With more than 330 palm oil mills in operation, Malaysia produces some 10.6 million tonnes of crude palm oil annually, accounting for 52% of the total world production, and concomitantly generates some 27 x 10^6 m^3 POME. To meet with the regulatory requirement, more than 85% of the mills use solely lagoon systems in wastewater treatment, typically anaerobic first stage followed by facultative treatment. Research data associated with this study revealed that methane yield ranging from 0.47 to 0.92 m^3kg^{-1}-BOD_{added} was attainable in the biomethanation of POME for reaction temperature of between 35 to 55 C. Considering the associated socio-environmental impact, an analysis of the research data indicates that about 375 x 10^6 m^3, or 225 Gg of CH_4 is evolved from open ponding systems used in POME treatment, accounting for 10% of the CH_4 inventory in Malaysia. In terms of greenhouse gas effect, this source amounts to 5,170 Gg in CO_2 equivalent, or 3.6% of the estimated total emissions in Malaysia. As methane can be harnessed for the generation of either thermal or electric energy, an economic assessment based on a life-cycle cost-benefit model as elucidated in this study shows that an annual return on investment of 31 to 58%, or payback period of 2.5 to 1.5 years, is possible in resource recovery systems utilising methane for heat generation and land application of digester effluent. The corresponding figures for electricity generation systems are 1.8 to 6.4% and 9.6 to 6.7 years. In the latter case, the palm oil industry as a whole would be in a position to potentially contribute 2,250 x 10^6 kWh annually, equivalent to about 4% of the national electricity demand. This compares favourably with the Malaysian Government policy to achieve 5% of the total electricity generation by 2005 from renewable bioenergy sources. In terms of thermal energy generation, the potential would be equivalent to 715 x 10^6 litres, worth some USD 120 million according to the prevailing price. Bioenergy recovery from the treatment of POME therefore not only contributes towards the sustainable growth of the palm oil industry, but also assists Malaysia in achieving its sustainable development objectives in connection with the United Nations Framework Convention on Climate Change.

1. INTRODUCTION

The palm oil industry has been expanding rapidly in the last three decades in Malaysia, with the planted area increasing by more than 11 fold from 291,000 ha in 1970 to 3,313,000 ha in 1999 [1]. Concomitantly, the number of palm oil mills has also grown from 122 in 1977 to 334 in 1999, having a total processing capacity of 69 million tonnes fresh fruit bunches (FFB) per year. Currently, Malaysia produces about 57 million tonnes of FFB annually, from which 10.6 million tonnes of crude palm oil and

1.3 million tonnes of palm kernel oil are extracted. In 1999, Malaysia exported 8.9 million tonnes of palm oil, and is currently ranked as the largest producer of palm oil in the world, accounting for 52% of the total world production. These figures put into perspective the importance of the palm oil industry in the overall industrial development of Malaysia.

The process to extract oil from the FFB requires voluminous amount of water, mainly for sterilising the fruits and for oil clarification, resulting in the discharge of about 2.5 m^3 of effluent per tonne of crude oil processed [2]. Thus in 1999, a total of about 26.5 million m^3 of effluent was generated from the Malaysian palm oil industry. Fresh palm oil mill effluent, or POME as it is popularly known, is an acidic brownish colloidal suspension characterised by high contents of organics and solids, and is discharged at a temperature of 80-90°C (Table 1). It has been estimated that POME contributes to about 30% of the total biochemical oxygen demand (BOD) load exerted on the Malaysian aquatic environment [3]. As one of the major sources of pollution, POME was among the first waste types to be singled out for statutory control. Table 1 also shows the regulatory discharge standards currently in force.

2. ANAEROBIC TREATMENT OF POME

2.1 The Status

In view of the high organic strength of POME, it has been recognised that first-stage treatment of the wastewater using anaerobic technology is the best option. Anaerobic digestion is a versatile biological treatment technology yielding methane as a useful bioenergy. In this respect, however, the majority, that is more than 85%, of the palm oil mills use solely ponding systems due to their low capital and operating costs [6] since most mills are situated in the plantations, and this situation has more or less been maintained through the years [4]. This is because the industry generally perceives that the installation of waste treatment systems is principally intended to satisfy statutory effluent discharge requirements. Only a few mills have reported the use and operation of closed-tank anaerobic bioreactors equipped with biogas recovery systems [7-10].

Table 1 Characteristics of raw POME(1) and the regulatory discharge limits

Parameter	Value(2)	Regulatory discharge limit(3)
Temperature (°C)	80-90	45
pH	4.7	5.0 - 9.0
Biochemical oxygen demand (BOD_3, 3 days at 30°C(4))	25,000	100 (50)(5)
Chemical oxygen demand (COD)	50,000	-
Total solids (TS)	40,000	-
Total suspended solids (TSS)	18,000	400
Total volatile solids (TVS)	34,000	-
Oil and grease (O&G)	4,000	50
Ammonia-nitrogen (NH_3-N)	35	150(6)
Total Kjeldahl nigrogen (TKN)	750	200(6)

(1) Ref. [4].

(2) All values, except pH and temperature, are expressed in mgL^{-1}.

(3) Ref. [5].

(4) Statutory incubation conditions.

(5) This additional limit is the arithmetic mean value determined on the basis of a minimum of four samples taken at least once a week for four weeks consecutively.

(6) Value of filtered sample

2.2 Environmental Considerations

Recent developments in global environmental issues, specifically relating to climate change which has identified the urgent need in reducing the emissions of greenhouse gases worldwide in order to control global warming, have prompted concern about methane generation from, among others, the anaerobic lagoons used in POME treatment. This is in line with the sustainable development objectives of Malaysia, which has ratified both the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. Furthermore, the new Fifth Fuel Policy of the Government of Malaysia in promoting renewable energy, in addition to the conventional energy sources of hydropower, natural gas, coal and oil, as an approach towards sustainable development has targeted achieving 5% of the total electricity production by 2005 [11], particularly through biomass resources, including biogas as a biofuel. Therefore, enhancing methane yield from the anaerobic treatment of POME represents another important consideration in harnessing this alternative energy source. In this connection, the inherently high discharge temperature of raw POME ranging from 80°C to 90°C should be advantageously exploited for biomethanation under thermophilic conditions, a situation that offers several potential advantages over mesophilic operation, including higher reaction rate and better process performance from the perspective of energy recovery, as well as improved solids dewatering and effective removal of pathogens from the environmental perspective [12].

2.3 Methane Yield

An earlier study [13, 14] revealed that methane production was significantly enhanced in the thermophilic compared with mesophilic digestion of POME. However, it appeared to be little affected by the 5°C rise in reaction temperature from 45°C to 50°C, while a substantial increase was conspicuous at 55°C. Table 2 lists the gas yields at the various temperatures studied. An increase of 42% and 53% in methane yield was noted when the digestion temperature was raised to 55°C from 45°C and 50°C respectively. Compared to mesophilic digestion, on the other hand, the methane yield was nearly doubled, with a 96% increase.

Table 2 Gas yields from anaerobic digestion of POME at various reaction temperatures

Reaction temperature (°C)	Biogas yield (m^3kg^{-1}-BOD_{added})	Mean CH_4 content (%)	CH_4 yield (m^3kg^{-1}-BOD_{added})
35	0.78	60	0.47
45	0.92	65	0.60
50	0.99	65	0.65
55	1.41	65	0.92

3. COST-BENEFIT ANALYSIS

3.1 Basis of Analysis

The economic evaluation of the biomethanation of POME takes into consideration the maximum utilisation of the biogas methane and the anaerobic liquor generated. It is based on an average-sized mill capacity of 45 tonnes FFB h^{-1} for 350 operating hours per month, or an annual crop throughput of 189,000 tonnes. The seasonal crop availability of oil palm for processing, befitting the said mill capacity, is estimated at 12,000 tonnes FFB $month^{-1}$ for 8 months during the trough period, and 22,500 tonnes FFB $month^{-1}$ for 4 months during the peak period, while the wastewater load ranges from 240 m^3d^{-1} to

450 m^3d^{-1} during the trough period and the peak period respectively, based on 25 working days per month. This is the range of hydraulic throughput for the anaerobic treatment system to be designed for this study.

Another consideration relating to land application of the anaerobically treated wastewater warrants that the effluent quality should not exceed 5,000 mgL^{-1} of BOD, which is the regulatory limit set [5]. To take cognizance of the significant temperature effects on the anaerobic digestion process as discussed above, it is useful to make a comparison of systems operated at digestion temperatures of 45°C, 50°C and 55°C. Table 3 lists the process parameters derived for the comparative economic analysis, which takes account of the capital and maintenance costs associated with and revenue generated from by-product utilisation accordingly. Although methane can be harnessed for the generation of both thermal and electric energy, particularly from the perspective of cogeneration, separate computations with respect to these two options, however, are carried out in this study.

Table 3 Process parameters for thermophilic anaerobic digestion of palm POME scaled for an average-sized mill as basis for economic evaluation

DESIGN BASIS			
Mill capacity (t-FFB h^{-1})			45
Wastewater load (m^3d^{-1})			240 – 450
Influent BOD (mgL^{-1})			25,000
Maximum digester effluent BOD (mgL^{-1})			5,000
OPERATING PARAMETERS			
Digestion temperature (°C)	45	50	55
Minimum retention time (d)$^{(1)}$	10.9	9.2	7.0
Minimum effective reactor volume$^{(1)}$ (m^3)	4,950	4,150	3,200
Hydraulic retention time (d)	20.6 – 11.0	17.3– 9.2	13.3 – 7.1
Expected digester effluent BOD (mgL^{-1})	1,230 – 4,890	2,500 - 5,000	2,320 – 4,910
BOD loading rate ($kgm^{-3}d^{-1}$)	1.21 – 2.27	1.45 – 2.71	1.88 – 3.52
Biogas production rate ($m^3m^{-3}d^{-1}$)	1.11 – 2.09	1.44 – 2.68	2.65 – 4.96
Annual biogas production (m^3)	2.56 x 10^6	2.77 x 10^6	3.94 x 10^6

$^{(1)}$ Kinetics-based computation [15].

3.2 The Concept

In carrying out the computations, reference is made to a model proposed by Gopal and Ma [16], which was based on the concept of life-cycle cost-benefit, or annualised cost-benefit over the economic life of the plant. The model is represented by:

$$C_{bl} = \sum_{t=1}^{t=n}\left[\frac{R_{ot}-C_{ot}}{(1+i)^t}-C_f\right]F_r = \sum_{t=1}^{t=n}\left[\frac{R_{ot}-C_{ot}}{(1+i)^t}-C_f\right]\frac{i(1+i)^n}{(1+i)^{n-1}} \quad (1)$$

where, C_{bl} = life-cycle cost-benefit (monetary unit),
R_{ot} = annual operating revenue at t^{th} year (monetary unit),
C_{ot} = annual operating cost at t^{th} year (monetary unit),
C_f = capital cost at base year (monetary unit),
F_r = capital recovery factor (capital charge factor),

i = interest rate (%),
n = economic life of the plant (year), and
t = t[th] year.

and where F_r is defined by:

$$F_r = \frac{i(1+i)^n}{(1+i)^{n-1}} \tag{2}$$

In view of the difficulty in determining inflationary and other uncertain factors which impact on the operating cost and revenue associated with the treatment plant operation, it is reasonable to assume constant values over the life span of the plant. This simplifies the model in Eq. (1) to an expression on annual cost-benefit by taking t as the base year.

$$C_{ba} = R_o - C_o - C_f \frac{i(1+i)^n}{(1+i)^{n-1}} \tag{3}$$

where, C_{ba} = annual cost-benefit (monetary unit),
R_o = annual operating revenue at base year (monetary unit), and
C_o = annual operating cost at base year (monetary unit).

In connection with this model, the other indices used in this economic evaluation are the return on investment and the simple payback period.

$$R_{oi} = \frac{C_{ba}}{C_f} x100 \tag{4}$$

where, R_{oi} = return on investment (%).

$$T_{pb} = \frac{C_f}{R_o - C_o} \tag{5}$$

where, T_{pb} = simple payback period (year).

3.3 Capital Costs and Annual Capital Charges

The capital cost of an anaerobic treatment system consists, in the main, of the anaerobic reactors and accessories, civil works, pump sets, piping and electrical works. Such data on actual full-scale operating plants have been scarcely reported in Malaysia, attributed to the few numbers of such plants in operation. It was reported [17] that two units of carbon-steel anaerobic digestion system with epoxy coating of 3,800 m^3 operating capacity, based on 1999 prices, cost RM 2,200,000 (equivalent to USD 580,000 @ USD 1.00 = RM 3.80 in 1999), compared to the reported cost data [9] of a full-scale plant comprising two anaerobic reactors with operating capacity of 4,200 m^3 each, costing in 1983 RM 1,010,000 (equivalent to USD 400,000 @ USD 1.00 = RM 2.50 in 1983). It is reasonable to use the 1999 unit price of USD 290,000 for an anaerobic reactor system of 3,800 m^3 operating capacity as the basis for cost computation of the required reactor sizes tabulated in Table 3, and scaled according to the findings of Hashimoto and Chen [18], who reported that the installed equipment cost of anaerobic digestion systems increased with the digester volume to the 0.7 power based on an analysis of actual plant installation costs, expressed by Eq. (6).

$$C_{reactor} = 2.9x10^5 \left(\frac{V_{reactor}}{3800} \right)^{0.7} \quad (6)$$

where, $C_{reactor}$ = computed cost of anaerobic digestion system (USD), and
$V_{reactor}$ = size of anaerobic reactor (m^3)

However, in arriving at the costs of the biomethanation systems, no provision was made for insulation cost, as calculations based on the steady-state digestion temperature model developed by Yeoh [19] revealed that the influent heat alone would be able to maintain the reactor temperatures very close to the desired temperatures. Some supplementary heating, where required, can be achieved without much difficulty and cost by tapping the abundantly available steriliser exhaust steam from the mill operation. Field data reported on the operation of two 3,700 m^3 non-insulated conventional CSTR digesters [20] indicated that the digestion temperature was maintained at 44-52°C by the inherent heat of the influent alone. It was also reported that the temperature variation over a day due to intermittent feeding was 2-3°C and over the weekend, when the digesters were not fed, a drop of about 4°C could occur. However, no operational difficulty had been experienced with these temperature fluctuations as reported.

The biogas storage system would comprise pressurised storage vessels, scrubbers, compressors, piping and housing. Based on the 1985 costs [9,16] of RM 220,000 (USD 88,000 @ USD 1.00 = RM 2.50) for a 2.12 x 10^6 m^3year^{-1} biogas system, and an annual inflation rate of 5%, the estimated costs (C_{biogas}, USD) at 1999 (based on USD 1.00 = RM 3.80) of biogas systems handling different gas volume capacities (V_{biogas}, m^3year^{-1}) on a linear regression basis would be:

$$C_{biogas} = \frac{V_{biogas}}{2.12x10^6} \frac{0.22x10^6}{3.8} (1.05)^{14} = 0.05407 V_{biogas} \quad (7)$$

In the case of utilising the biogas for electric power generation, additional cost would be incurred in the installation of gas-engine generators. It was reported [10] that biogas containing 54-70% CH_4 was consumed at a rate ranging from 0.55 to 0.41 $m^3(kWh)^{-1}$ in a 250-kW generator in one palm oil mill. In another operation also using a 250-kW generator, it was reported that the mean biogas consumption by the gas-engine as recorded by a gas flow-meter was 0.50 $m^3(kWh)^{-1}$ [9]. These results compared favourably with another report of 0.75 $m^3(kWh)^{-1}$ in a farm operation using small generators of capacities ranging between 3.0 and 7.5 kW [21]. Therefore, based on the biogas consumption of 0.50 $m^3(kWh)^{-1}$, biogas generated from the 45°C, 50°C 55°C systems (Table 3) would potentially generate a gross output of 5.12, 5.54 and 7.88 x 10^6 kWh $year^{-1}$ respectively. Assuming 8,300 operating hours per year after making allowance for routine maintenance stoppage, the appropriate electricity generation capacity to be installed for the 45°C, 50°C 55°C systems would be 620, 670 and 950 kW respectively. The price for one unit of 250-kW gas-engine generator was estimated at USD 250,000. It would be reasonable to derive the capital cost of electricity generation for the three said systems to be USD 620,000, 670,000 and 950,000 respectively.

In computing the cost of land application of the digester effluent, which included construction works and equipment installation relating to the distribution system, it was based on an optimal application rate of 6.7 cm rain equivalent per year [10]. For an average-sized palm oil mill as described in Table 3, the total wastewater throughput for 25 operating days per month would be 240 x 25 x 8 + 450 x 25 x 4 = 93,000 m^3year^{-1}. Therefore 93,000 / (0.067 x 10,000) = 139 hectares of plantation land would be covered. The land application systems that are commonly used in oil palm plantations include the flat-bed system for hilly terrain, the long-bed system for relatively flat terrain, and the sprinkler system which is portable or semi-portable [22-27]. The reported capital costs of these systems ranged from RM 1,400 to RM 1,800 per hectare at around 1982-1985 [9, 10, 24, 27]. Taking the median of RM 1,600 per hectare and an annual inflation rate of 5%, the estimated capital cost of the land application system (C_{land}, monetary unit) for 139 hectares at 1999 would be RM 1,600 x 139 x $(1.05)^{15}$ = RM 462,350 (USD 121,670 @ USD 1.00 = RM 3.80).

In computing the total capital costs, land cost was not included in the computation. The anaerobic treatment system and the gas storage system would occupy a maximum land area of 2.0 ha, which is negligible as most palm oil mills are situated in the plantations where land availability is not a constraint.

The capital charges consist of two components, namely the financial cost of fixed capital (C_{fc}, monetary unit) computed according to Eq. 8 below, and the depreciation cost (C_d, monetary unit) based on a 15-year straight-line depreciation of the total capital costs

$$C_{fc} = C_f F_r = C_f \frac{i(1+i)^n}{(1+i)^{n-1}} \qquad (8)$$

$$C_d = \frac{C_f}{15} \qquad (9)$$

3.4 Annual Operating and Maintenance Costs

The annual operating costs cover, in the main, labour, consumables, and utility, while the annual maintenance cost is usually estimated as a percentage of the installed equipment cost.

In estimating the labour cost, salaries for the plant operators were fixed at RM 42,000 per annum for an engineer and RM 15,000 per annum for a technician or an operator. Utility cost was principally associated with the energy requirement for equipment operation, and the electricity rate was fixed at RM 0.25 per kWh. The basis for computations is listed in Table 4.

In computing the maintenance costs, essentially three categories were considered, namely the anaerobic treatment system including biogas handling, the gas-engine generator system, and the land application system for digester effluent. For the anaerobic system, it was reported that [9, 16] that the annual maintenance costs based on actual full-scale plants were 2.8% and 3.8% respectively of the installed equipment costs. Hashimoto and Chen [18] used a figure of 3%, which was also adopted in the economic analysis of biomass energy cogeneration systems [17]. It was therefore reasonable to compute the annual maintenance cost in this study based on 3% of the capital cost in biomethanation. Maintenance of the gas-engine generator was reported to be 3.9%-5.6% [9, 16]. A figure of 5% was therefore used in this appraisal. For the land application system, the maintenance costs reported ranged between 1.7% and 2.3% of the capital costs [10, 16, 27], indicating that 2% would be practical.

Table 4 Basis for computation of labour and energy costs

Operation	Labour requirement	Energy requiremen(1)	
		Equipment	Power
Wastewater treatment	1 operator	Gas recirculation, pumps	30 kW
Biogas storage	1 operator	Compressors	20 kW
Electricity generation	1 engineer, 2 technicians	-	-
Land application	2 operators	Pumps	25 kW

(1) The energy requirement is based on off-milling period of 4,560 hours per year, assumed to be supplied by generators. During mill operation (14 hours x 300 days = 4,200 hours per year), the energy is supplied by the mill steam turbine.

3.5 Annual Operating Revenue

The revenue to be derived from by-product utilisation in the anaerobic treatment system is associated with energy recovery from the biogas methane generated and nutrient recovery from the digester effluent.

Biogas containing 65% methane has a heating value of 22.4 MJm^{-3} [28], while the calorific value of diesel or fuel oil is 34.5 MJL^{-1} [29]. Therefore, in terms of thermal energy generation, 1 m^3 of biogas is equivalent to 0.65 L of diesel or fuel oil, valued at RM 0.42, based on the average price of diesel or fuel oil at RM 0.65 in 1999 [17].

In converting biogas to electrical energy using gas-engine generators, the appraisal was based on the biogas consumption of 0.50 $m^3(kWh)^{-1}$ as discussed above. On the other hand, 1 kWh of electricity would be generated by 0.34 L diesel [30]. Referring to the average price of diesel at RM 0.65 in 1999, 1 m^3 biogas used in electrical energy generation was therefore valued at RM 0.442 in this assessment with the assumption that it would substitute diesel as fuel for the generators. This appears to be more attractive compared to using biogas for direct thermal energy generation. On the other hand, the gas-engine generator would require an auxiliary power demand for the compressor and cooling system at about 12% of its gross power generation, giving a net power output of 88% of its rated capacity [16]. Therefore, the 45°C, 50°C and 55°C systems would generate a net output of 4.51, 4.88 and 6.93 x 10^6 kWh respectively, with reference to the computation above. In accordance with the above discussion, this electrical output would be valued at RM 0.221 per kWh.

Extensive field studies [10] revealed that anaerobically digested POME was able to completely replace inorganic fertilisers on oil palms. Experiments using both the flat-bed and sprinkler systems of land application with application rates ranging from 3.3 to 13.3 cm rain equivalent per year resulted in increased FFB yield of 10% to 23% over the control using normal inorganic fertilisers. It was estimated that the fertiliser saving would amount to RM 943 per hectare. A nominal 10% increase in FFB yield would result in an additional 1.93 tonnes FFB $ha^{-1}year^{-1}$, based on the average yield of 19.26 tonnes FFB ha^{-1} in 1999 [1]. This would give a value of RM 504, estimated on the basis of RM 261 per tonne FFB on an average crude palm oil price of RM 1,449.50 in 1999 [1].

3.6 Cost-Benefit Computation

Table 5 shows the cost-benefit analysis on systems utilising biogas for thermal energy generation, taking into account all the considerations discussed in the above sections. The assessment indicates that there is substantial annual return on investment from the anaerobic treatment systems, which is particularly enhanced in the 55°C reactor system with a 58% return, representing 91% and 56% higher than the 45°C and 50°C systems respectively. In terms of simple payback, all the three systems offer great attractiveness as a sound waste management technology with resource recovery, all within 2.5 years.

On the other hand, the analysis on systems harnessing biogas for electric energy generation, as shown in Table 6, reveals that the benefits acquired from the treatment systems are very much reduced, although the annual operating revenue derived from the electricity generation systems is still comparable to that of the heat generation systems. This is due mainly to the considerably higher capital costs of the equipment involved in the former, resulting in substantially increased capital charges and depreciation cost. However, payback periods of 5 to 7 years are considered normal for biomass-based renewable energy systems for electricity generation [17]. The annual return on investment of 3 to 6% in the 50°C and 55°C systems is still considered to be reasonable, bearing in mind that the costs of wastewater treatment, which is a regulatory requirement, have already been accounted for. The 55°C system is again shown to be a worthy option in terms of the cost-benefits generated.

3.7 Limitations

It is evident from the above evaluation, in broad quantitative terms, that utilisation of by-products, notably methane, from the anaerobic treatment of POME brings about significant economic gains. Although the final financial figures related to the thermal conversion systems are much more attractive than the electrical conversion systems, the revenue generated from both these conversions of biogas into energy forms the bulk of the total operating revenue, being 83% to 89%. Therefore, it is imperative from the economic perspective to positively enhance the treatment efficiency and methane yield in POME treatment.

It is to be emphasised that this assessment assumes full, or at least high, utilisation of the methane produced, which may not be easily achievable. This is because the palm oil milling operation is largely self-sufficient in terms of energy through the use of the waste solid biomass, namely fibre and shell, for energy generation as traditionally practised. Consequently, the methane produced from the effluent treatment plant may represent an energy source in excess of the mill's requirement. The economics of the anaerobic treatment system, as a revenue source, therefore depends much on the extent and the form of the biogas use, particularly for off-site utilisation.

The economic evaluation should be viewed as a guide to the comparative cost-benefits of resource recovery from the anaerobic treatment of POME. Although it does provide an enhanced analysis of the effects of digestion temperature and the mode of methane utilisation on the biomethanation system through the translation from technical terms to tangible economic terms, the figures quoted are essentially best practical estimates. This is because some factors, such as operational variability and inflationary effects on costs and revenues beyond the base year have not been considered. Furthermore, the benefits arising from methane utilisation, in particular, are very sensitive to the actual value of the energy form that is substituted for, which may vary considerably from case to case.

Table 5 Cost-benefit analysis of anaerobic treatment of POME with resource recovery: Systems utilising biogas for heat generation and land application of digester effluent(1)

Reactor temperature (°C)	45	50	55
Capital cost, $C_f = C_{reactor} + C_{biogas} + C_{land}$	609,050	579,890	591,840
Anaerobic reactor system, $C_{reactor}$ (Eq. 6)	348,960	308,450	257,130
Biogas storage system, C_{biogas} (Eq. 7)	138,420	149,770	213,040
Land application system, C_{land}	121,670	121,670	121,670
Annual capital charges(2), C_{fc} (Eq. 8)	52,620	50,100	51,130
Annual operating and maintenance cost, C_o = i + ii + iii + C_d	95,950	93,130	94,290
Anaerobic treatment (i)	23,420	22,200	20,660
Biogas handling (ii)	14,100	14,440	16,340
Land application (iii)	17,830	17,830	17,830
Equipment depreciation, C_d (Eq. 9)	40,600	38,660	39,460
Annual operating revenue, R_o = A + B + C	335,880	359,090	488,400
Biogas utilisation (A)	282,950	306,160	435,470
Fertiliser saving (B)	34,490	34,490	34,490
Increased FFB yield (C)	18,440	18,440	18,440
Annual cost-benefit, $C_{ba} = R_o - C_o - C_{fc}$ (Eq. 3)	187,310	215,860	342,980
Annual return on investment, $R_{oi} = (C_{ba}/C_f) \times 100$ (Eq. 4) (%)	30.8	37.2	58.0
Payback period, $Tpb = C_f/(R_o - C_o)$ (Eq. 5) (year)	2.5	2.2	1.5

(1) All figures, except otherwise stated, are in USD equivalent (based on USD 1.00 = RM 3.80).

(2) Based on interest rate i = 8% per annum for n = 15 years.

Table 6 Cost-benefit analysis of anaerobic treatment of POME with resource recovery: system utilising biogas for electricity generation and land applicationof digester effluent[(1)]

Reactor temperature (°C)	45	50	55
Capital cost, $C_f = C_{reactor} + C_{biogas} + C_{land} + C_{generator}$	1,229,050	1,249,890	1,541,840
Anaerobic reactor system, $C_{reactor}$ (Eq. 6)	348,960	308,450	257,130
Biogas storage system, C_{biogas} (Eq. 7)	138,420	149,770	213,040
Land application system, C_{land}	121,670	121,670	121,670
Gas-engine generators, $C_{generator}$	620,000	670,000	950,000
Annual capital charges[(2)], C_{fc} (Eq. 8)	106,190	107,990	133,210
Annual operating & maintenance cost, C_o = i + ii + iii + iv + C_d	187,240	191,130	224,590
Anaerobic treatment (i)	23,420	22,200	20,660
Biogas handling (ii)	14,100	14,440	16,340
Land application (iii)	17,830	17,830	17,830
Electricity generation (iv)	49,950	52,450	66,450
Equipment depreciation, C_d (Eq. 9)	81,940	83,330	102,790
Annual operating revenue, R_o = A + B + C	315,220	336,740	455,960
Biogas utilisation (A)	262,290	283,810	403,030
Fertiliser saving (B)	34,490	34,490	34,490
Increased FFB yield (C)	18,440	18,440	18,440
Annual cost-benefit, $C_{ba} = R_o - C_o - C_{fc}$ (Eq. 3)	21,790	37,620	98,160
Annual return on investment, $R_{oi} = (C_{ba}/C_f)x100$ (Eq. 4) (%)	1.8	3.0	6.4
Payback period, $Tpb = C_f/(R_o - C_o)$ (Eq. 5) (year)	9.6	8.6	6.7

(1) All figures, except otherwise stated, are in USD equivalent (based on USD 1.00 = RM 3.80).

(2) Based on interest rate i = 8% per annum for n = 15 years.

4. PROSPECTS FOR COMMERCIALISATION

4.1 Policy Aspects

Notwithstanding the aforementioned limitations, there have recently been very positive and important developments in Malaysia associated with this subject. The main energy sources for the generation of electricity have traditionally been natural gas (71%), fuel oil and diesel (8%), hydro (12%) and coal (9%) based on 1999 statistics [31] (Department of Electricity and Gas Supply Malaysia, 2000). In 1999, the total installed power generation capacity in Malaysia was 13.632 GW, while the power demand was 9.961 GW. Projections show that electricity demand in the country will grow by 6-10% annually.

The Government of Malaysia has formulated a strategy for renewable energy as the fifth fuel in addition to the aforementioned conventional energy sources as an approach towards sustainable development. This recognition by the Government of the importance and contribution of renewable energy in the total energy equation of the country is the most significant first step in initiating and implementing renewable projects [32]. A holistic approach is adopted in promoting the utilisation of renewable resources including biomass, biogas, solar and mini-hydropower. This effort is being intensified in the Fifth Malaysia Plan (2001-2005), particularly with respect to biomass resources, including biogas, for the purpose of heat and electricity generation, with the target of achieving a contribution of 5% of the total electricity production (amounting to 500 MW) by 2005 [11]. Towards this end, the Ministry of Energy, Communications and Multimedia Malaysia launched a “Small Renewable Energy Programme” (SREP) in May 2001 to provide specific economic incentives for the promotion of small electricity generation plants of less than 10 MW capacities for grid connection, using renewable energy resources, predominantly biomass resources including biogas. In addition, following Malaysia's ratification of the Kyoto Protocol, infrastructure is being put in place to prepare for the implementation of the Clean Development Mechanism (CDM).

Methane generation from the anaerobic treatment of POME represents one of the significant sources of greenhouse gases in Malaysia, particularly from the open ponding systems currently being used widely in the palm oil industry. Assuming a proximate lagoon temperature of 35°C, the potential methane production from POME in 1999 from open ponding systems would amount to 375 x 10^6 m^3 (Table 7), or 225 Gg, taking the density of CH_4 as 0.6 kgm^{-3}. In comparison, the total CH_4 emissions from all categories in Malaysia were estimated at 2,231 Gg in 1994, the adopted reference year for the inventory of greenhouse gas emissions [33]. Methane is about 21 times more potent than carbon dioxide in terms of its global warming potential, and the estimated CO_2 content in the biogas generated from POME was 247 x 10^6 m^3 (or 445 Gg taking the density as 1.8 kgm^{-3}) in 1999 (based on Table 2); therefore, the said biogas source amounted to 5,170 Gg in CO_2 equivalent in terms of its greenhouse effect. The aforementioned report [33] estimated the total greenhouse gas emissions in Malaysia at 144,314 Gg in CO_2 equivalent in 1994. Maximising the conversion of biogas methane from the anaerobic treatment of palm oil mill effluent to energy therefore satisfies both environmental and economic considerations.

4.2 Energy Potential

In view of the positive developments, there is growing awareness in the Malaysian palm oil industry of the viability of anaerobic digestion and the attractive economic value of its by-products, as the this study has revealed. Table 7 shows the potential bioenergy recuperable from POME digested at various temperatures based on the status in 1999. Taking the optimal digestion temperature of 55°C in accordance with this study, it was equivalent to 715 million litres of fuel oil in terms of thermal energy, worth some USD 120 million at the 1999 price in Malaysia. In terms of electric energy obtainable through the use of gas-engine generators, it would generate 2,250 million kWh, contributing to about 4% of the national electricity demand in 1999, based on the total demand of 56,400 million kWh [34]. Therefore, if the wastewater produced by the palm oil industry were to be totally treated by thermophilic anaerobic digestion at 55°C with the biogas fully recovered for electric energy generation, it would satisfy almost the Government's target of achieving 5% of the total electricity production from this source alone. This compares much favourably with digestion carried out mesophilically, which would otherwise contribute only 2%. Undoubtedly, these benefits will be positively enhanced in cogeneration systems where both thermal and electric energy are generated simultaneously.

Table 7 Energy potential of POME digested at various temperatures(1)

Digestion temp. (°C)	Methane production(2) (x 10^6 m^3year^{-1})	Thermal energy obtainable(3) (x 10^{15} $Jyear^{-1}$)	Fuel oil equivalent (x 10^6 $Lyear^{-1}$)	Electricity obtainable(4) (x 10^6 $kWhyear^{-1}$)
35	375	12.94	365	1,240
45	479	16.53	467	1,470
50	518	17.87	505	1,580
55	734	25.32	715	2,250

(1) Based on FFB production of 63.8 x 10^6 tonnes in 1999 [1]. Estimated total volume of wastewater generated from the processing of FFB was 31.9 x 10^6 m^3.

(2) Computed according to Table 2, taking a mean raw wastewater BOD of 25,000 mgL^{-1}.

(3) Taking calorific value of methane as 34.5 x 10^6 Jm^{-3}.

(4) Based on biogas consumption of 0.50 $m^3(kWh)^{-1}$ using gas-engine generators.

5. REFERENCES

[1] Ministry of Primary Industries Malaysia. 2000. Statistics on Commodities 2000.

[2] Ma, A.N. and Ong, A.S.H. 1988. Treatment of palm oil steriliser condensate by an anaerobic process. *Biol. Wastes* 23: 85-97.

[3] Yeoh, B.G.; Idrus, A.Z.; and Ong, K.S. 1988. Technology research and development for environmental management - with specific reference to Malaysia. *ASEAN Jour. Sci. Technol. Develop.* 5(1): 1-13.

[4] Ma, A. N. 2000. Management of palm oil industrial effluents. *Advances in Oil Palm Research*. Bangi: Malaysian Palm Oil Board, Ministry of Primary Industries Malaysia, Chap. 34: 1439-1461.

[5] Government of Malaysia. 1977. Environmental Quality (Prescribed Premises) (Crude Palm Oil) Regulations 1977. P.U.(A) 342/1977, amended by P.U.(A) 183/82.

[6] Ma, A.N. and Ong, A.S.H. 1985. Pollution control in palm oil mills in Malaysia. *J. Amer. Oil Chem. Soc.* 62: 261-266.

[7] Gillies, D. and Quah, S.K. 1984. Tennamaram biogas project. In *Proceedings of Second ASEAN Workshop on Biogas Technology*. Kuala Terengganu, Malaysia, ASEAN Committee on Science and Technology: 277-292.

[8] Chua, N.S. and Gian, H.L. 1986. Biogas production and utilization - Keck Seng's experience. In *National Workshop on Recent Developments in Palm Oil Milling Technology and Pollution Control*. Kuala Lumpur, Malaysia, Bangi: Palm Oil Research Institute of Malaysia, Paper No. 11 .

[9] Quah, S.K. 1987. Chan Wing palm oil mill effluent treatment and by-product utilisation - a case study. Lecture Notes for Training Course on Biogas Reactor Design and Development. Bangkok, King Mongkut's Institute of Technology Thonburi, 2: 562-584.

[10] Lim, K.H. 1988. Integrated systems for treating and utilizing plantation effluents: palm oil mill effluent as a specific example. *Anaerobic Digestion 1988*. Oxford: Pergamon Press: 303-313.

[11] Prime Minister's Department Malaysia. 2001. *Eighth Malaysia Plan 2001-2005*. Chap. 11.

[12] Wiegant, W.M. 1986. Thermophilic anaerobic wastewater treatment. In *Anaerobic Treatment: A Grown-up Technology*, *Conference Papers, Aquatech '86*. Schiedam, Industrial Presentations: 115-127.

[13] Yeoh, B.G.; Chew, T.Y.; Ma, A.N.; Cheah, S.C.; Chow, M.C.; Raj, R.; Ibrahim, A.; and Wahid, M.J.A. 1986. Improved anaerobic digestion of palm oil mill effluent using the thermophilic contact process. In *National Workshop on Recent Developments in Palm Oil Milling Technology and Pollution Control*. Kuala Lumpur, Malaysia, 5-6 August, Bangi: Palm Oil Research Institute of Malaysia, Paper No. 10.

[14] Yeoh, B.G. 1988. Anaerobic wastewater treatment pays: case of a strong agroindustrial effluent. *Anaerobic Digestion 1988*. Oxford: Pergamon Press: 315-324.

[15] Yeoh, B.G. 1986. A kinetic-based design for thermophilic anaerobic treatment of a high-strength agroindustrial wastewater. *Environ. Technol. Lett.* 7: 509-518.

[16] Gopal, J. and Ma, A.N. 1986. The comparative economics of palm oil mill effluent treatment and resource recovery systems. In *National Workshop on Recent Developments in Palm Oil Milling Technology and Pollution Control*. Kuala Lumpur, Malaysia, Bangi: Palm Oil Research Institute of Malaysia, Paper No. 14.

[17] Pusat Tenaga Malaysia. 2000. Feasibility Study on Grid Connected Power Generation Using Biomass Cogeneration Technology.

[18] Hashimoto, A.G. and Chen, Y.R. 1979. The overall economics of anaerobic digestion. *Anaerobic Digestion*. London: Applied Science Publishers: 449-466.

[19] Yeoh, B.G.; Roslan, M.Y.; and Quah, S.K. 1991. Optimising methane yield in anaerobic POME treatment through temperature and process manipulations. *J. Indus. Technol*. 1(1): 19-31.

[20] Quah, S.K. and Gilles, D. 1981. Practical experience in production and use of biogas. In *Proceedings of National Workshop on Oil Palm By-Product Utilisation*. Kuala Lumpur, Malaysia, Bangi: Palm Oil Research Institute of Malaysia: 119-125.

[21] Zexi, C. 1984. Application of biogas on farm internal combustion engine. *Renewable Energy Resources: International Progress*. Amsterdam: Elsevier Science, Part B: 69-86.

[22] Kanagaratnam, J.; Lai, A.L.; Lim, P.; and Wood, B.J. 1981. Application methods of digested palm oil mill effluent in relation to land characteristics and oil palm crop. In *Proceedings of National Workshop on Oil Palm By-Product Utilisation*. Kuala Lumpur, Malaysia, Bangi: Palm Oil Research Institute of Malaysia: 16-22.

[23] Quah, S.K.; Lim, K.H.; Gillies, D.; Wood, B.J.; and Kanagaratnam, J. 1982. Sime Darby POME treatment and land application systems. In *Regional Workshop on Palm Oil Mill Technology and Effluent Treatment*. Kuala Lumpur, Malaysia.

[24] Lai, A.L.; Lim, K.H.; Wood, B.J.; and Kanagaratnam, J. 1982. Design and operating approaches to land application of palm oil mill effluent on major plantation crops. *Technology, Utilization and Management of Agricultural Wastes*. Serdang, Universiti Pertanian Malaysia: 199-211.

[25] Lim, K.H.; Wood, B.J.; Lai, A.L.; Wan Sulaiman, W.H.; and Mohamed, S. 1983. Land application of digested POME supernatant on oil palm using a flatbed system. In *Seminar on Land Application of Palm Oil and Rubber Factory Effluents*. Kuala Lumpur, Malaysia.

[26] Lim, C.H.; P'ng, T.C.; Chan, K.W.; and Chooi, S.Y. 1983. Land application of digested palm oil mill effluent (POME) by sprinkler system. In *Seminar on Land Application of Palm Oil and Rubber Factory Effluents*. Kuala Lumpur, Malaysia.

[27] Yeow, K.H. and Yeop, A.K. 1983. The present status of effluent utilisation in Malaysia. In *Proceedings of RRIM Planters' Conference 1983*. Kuala Lumpur, Malaysia, Kuala Lumpur, Rubber Research Institute of Malaysia: 347-367.

[28] Metcalf & Eddy 1991. *Wastewater Engineering: Treatment, Disposal and Reuse*. New York: McGraw-Hill, 826 p.

[29] Constant, M.; Naveau, H.; Ferrero, G. L.; and Nyns, E. J. 1989. *Biogas End-Use in the European Community*. London: Elsevier Applied Science, 18 p.

[30] Salam, B.A. 1985. The contribution of the oil palm by-products towards the national energy policy - an economist point of view. In *Proceedings of the National Symposium on Oil Palm By-Products for Agro-based Industries*. Kuala Lumpur, Malaysia, Bangi: Palm Oil Research Institute of Malaysia: 133-145.

[31] Department of Electricity and Gas Supply Malaysia. 2000. *Statistics of Electricity Supply Industry in Malaysia*. 2000 Edition.

[32] Dansk Energi Management A/S. 2000. Support to the Development of a Strategy for Renewable Energy as the Fifth Fuel in Malaysia. Economic Planning Unit, Prime Minister's Department Malaysia. Output 1: Short Draft Background Paper.

[33] Ministry of Science, Technology and the Environment Malaysia. 2000. Malaysia Initial National Communication. *Submitted to the United Nations Framework Convention on Climate Change*.

[34] Ministry of Energy, Communications and Multimedia Malaysia. 2000. National Energy Balance Malaysia (1980-1999).