Points to Consider in Biomass-Based Grid Connected RE Power Plant Design

N Ravi Menon*; Nasrin Abu Bakar* and Endang Jati**

INTRODUCTION

In designing a palm oil mill biomass-based grid connected power station, the prevailing design thinking has to give way to a different concept in order to avoid the possibility of making costly errors. The common mistakes among others generally stem from the wrong selection of boiler pressure, turbine exhaust vacuum and fuel treatment, storage and handling. The following considerations must be kept in mind when thinking of setting up RE power plant projects:

- the power plant must be able to convert maximum possible electrical energy from palm oil mill biomass. The design engineer should not be influenced by the overall thermal efficiencies of the existing steam power plants in palm oil mills. The boilers in these mills were deliberately designed not only to produce sufficient steam and power for the operation of the mill but also to serve as an incinerator to cut down the disposal cost of the surplus biomass.

- they must aim for a high boiler pressure of 40-60 bar, subject to other considerations and a high vacuum of not less than 0.1 bar (absolute), if the state point after isentropic expansion at the turbine exhaust does not cause the pressure point to drift too far into the wet region below the normally acceptable dryness fraction of 0.9. Boiler pressures exceeding 45 bar may not be possible if empty fruit bunches (EFB) is the only fuel available as fuel for the boiler due to the high potash content in the ash and its damaging effect on the boiler parts.

- as all steam engineers are aware, the use of steam purely for power production can only give a Rankine efficiency close to 40%, the design engineer should also consider the possibility of combined heating and power production as this can give much higher efficiencies. For this, an extraction turbine seems to be the best compromise. The millers who want to retrofit RE power plants in their mill power plants may use the EFB for their existing boilers and spare the shell and fibre for the RE power plant. In this case, the mill needs to use only one of their boilers as the bled steam from the condensing turbine can complement the mill process heating requirement.

*Malaysian Palm Oil Board,
P.O. Box 10620,
50720 Kuala Lumpur,
Malaysia.

**Pusat Tenaga Malaysia,
Level 8, North Wing Bangunan SAPURA@MINES,
7 Jalan Tasik, The Mines Resort City,
43300 Seri Kembangan, Selangor,
Malaysia.

- as the bled steam may become surplus during non-processing hours, this steam can be profitably utilized in many ways like (a) storing up in a steam accumulator, (b) fuel pre-heating, (c) feed water heating or (d) air pre-heating; all of which can contribute towards increased plant efficiency.

- the capital investment needed for setting up the power plant should take into consideration the economic viability of the investment. The payback period should be such that it should attract commercial banks to finance similar biomass-based power plant projects without hesitation.

- the biogas generated by the effluent digestion ponds is a greenhouse gas (GHG) and it is currently discharged to the atmosphere without any restriction. This is considered to be 24 times more harmful than CO_2 as a gas and it has become a global issue. An efficient method to harness this gas (comprising about 65% methane, 35% carbon dioxide and traces of hydrogen sulphide and chlorine) and convert it to electrical energy either in a boiler or other means have to be considered.

ANALYSIS OF A RETROFITTED CONVENTIONAL RE POWER PLANT

Let us have a look at a mill processing 60 t hr^{-1} fresh fruit bunch (FFB) using a non-extraction condensing turbine. Based on 360 000 t FFB processed by the mill per year, the following computation are made with reasonable level of accuracy based on the generally accepted figures in the industry. The figures are susceptible to fluctuations particularly the degree of development of the fruit itself. The mesocarp thickness of the fruit depends very much on fertilization and rainfall and hence to be on the safe side, conservative figures are used in this article and it is possible to get a higher energy output in an actual plant than this computation.

The calorific values also can vary based on the moisture and oil content of the biomass components. The lower calorific values (net) are given in *Table 1*.

Biomass Components and their Ratios

In order to evaluate the fuel and the energy available for grid connected power generation, the quantity of biomass requirement need to be evaluated. These are given in *Table 2*. The figures used are conservative figures. The normally accepted values are given in brackets. But

TABLE 1. CALORIFIC VALUE (net) OF PALM OIL BIOMASS PRODUCTS (kJ kg^{-1})

Moisture	Shell		Fibre		Empty fruit bunch	
	Pure	Oily	Pure	Oily	Pure	Oily
0	20 720	20 930	19 670	20 720	17 580	18 836
10	17 245	18 836	—	—	—	—
40	—	—	10 778	11 344	—	—
50	—	—	8 312	9 134	7 354	8 162
60	—	—	—	—	5 525	6 028

TABLE 2. THE QUANTITY (%) OF BIOMASS FRESH FRUIT BUNCH (FFB)

FFB (360 000 t)	Empty fruit bunch	Fibre	Nuts	Shell 5.5 (6%)	
				Dry shell 70%	Wet shell 30%
Percentage	22% (23%)	12% (14%)	11% (12%)	3.85% (4.2%)	1.65% (1.8%)
Quantity	79 200 t	43 200 t	39 600 t	13 860 t	5 940 t

again the millers are urged to verify these figures using a professional consultant.

FUEL REQUIREMENT OF THE MILL – EXISTING SYSTEM

Out of the biomass available in the mill, almost the entire dry shell is currently utilized by the mill for generating power and process steam heating. The mill boilers commonly use a mixture of fibre and shell as the boiler fuel in the ratio of 70:30 but this is not necessarily so in all mills. Some mills use EFB as well, when they are in short supply of regular fuels. The fuels are not generally pre-treated in palm oil mills.

The fuel available for grid-connected power generation will therefore be the whole of EFB, all the wet shell and say about 15% of the fibre/shell mixture. The energy computation based on a 60 t FFB hr^{-1} palm oil processing mill is shown in *Table 3*.

TABLE 3. ANALYSIS OF BIOMASS ENERGY POTENTIAL

FFB processed 60 t hr^{-1}	Fibre 12%	Dry shell 3.5%	Wet shell 1.65%	FFB 22%	Total
Production rate (t hr^{-1})	7.2	2.31	0.99	13.2	—
Mill boiler feed rate (t hr^{-1})	6.48	2.19	nil	nil	—
Balance for RE (t hr^{-1})	0.72	0.12	0.99	13.2	—
Calorie value (net) (kJ) kg^{-1}) at moisture level %	11 344 40	20 720 0	17 245 10	6 593 65	—
Heat input to boiler (MJ)	7.10	45 377	nil	nil	118 887
Heat available for RE (MJ)	8 168	2 486	17 073	87 028	114 755

Let us now evaluate the overall thermal efficiency of the mill power plant, ignoring the process heating steam.

Boiler steam pressure : 22 bar (absolute) super heated
Turbine exhaust steam pressure : 4 bar (absolute) 0.86 dry

Heat input :
Assumptions :
Fuel for mill power generation : 90% of the fibre and 95% of the dry shell:

A 60 t FFB hr^{-1} mill will require about 1 MW electrical power
Heat input to the boiler for raising steam = 118 882 MJ
Power potential of this is = 33 MW

Thermal efficiency for power generation = 3% (ignoring process heating)

RE power potential from 114 755 MJ = 31.88 MW

At a thermal efficiency of 25% actual power output = 7.97 MW

This figure is based on 100% utilization factor. In actual fact, utilization factor will be about 70%, in which case, the power plant capacity will rise to about 11 MW.

Biogas Exploitation

It is estimated (need confirmation) that 28 m^3 of biogas can be generated from every cubic metres of palm oil mill effluent in effluent digestion pond. If this is true,

POME production rate at 65% to FFB = 39 m^3

Biogas production rate at 28 m^3 POME = 1092 m^3

The calorific value (lower C.V.) of the biogas ranges from 17 829 to 23 130 kJ m^{-3}, giving an average value of 20 000 kJ m^{-3}.

Energy available as heat input to boiler = 21 840 MJ

Electrical output at 25% efficiency = 5460 MJ

= 1.52 MWhr

The power plant capacity = 1.52 MW

If gas engine driven alternators are used, higher efficiencies are possible:

Total power potential = 7.97 + 1.52 = 9.41 MW

If auxiliary load is 12%, power available for grid supply is 8.35 MW

SELECTION OF BOILER PARAMETERS

It is generally accepted that the high end pressure rating for a medium pressure steam boiler is 42 bar-a without much metallurgical problems arising from high pressures and associated stress. As high boiler pressures give high thermal efficiencies, it is prudent to select the best available pressure within metallurgical limits. The steam pressures currently used in a conventional palm oil mill boiler are 22 bar (abs) boiler pressure and turbine exhaust pressure of 4 bar (abs) giving a pressure ratio of 5.5 with the result that the thermal efficiency is only in the region of 3%.

As an example, if we select a boiler pressure of 42 bar (abs) and a condenser pressure of 0.1 bar (abs) the pressure ratio is 420. Superheating of the steam at this pressure will not only increase the overall thermal efficiency of the boiler but also offer a significant improvement in specific steam consumption. There are of course better cycles than this, offering less specific steam consumption and the reader is encouraged to work out a number of cycles for the pleasure of finding out the best one for maximum output.

At a superheat temperature of 500°C, the total enthalpy of steam is 3443 kJ kg^{-1}. Isentropic expansion of this steam in a turbine to a condenser pressure of 0.1 bar (abs) will also give a reasonably comfortable dryness factor of 0.85.

If these power plant parameters are adopted, theoretically it is possible to operate the plant with a specific steam consumption of less than 3 kg $kWhr^{-1}$. A simple thermodynamic cycle is shown in *Figure 1.*

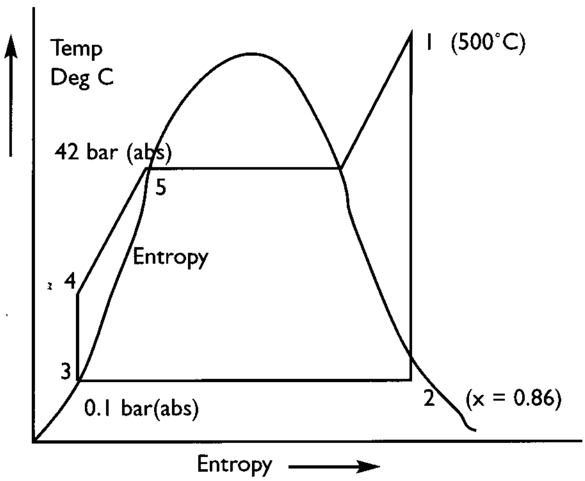

Figure 1. Temperature-entropy diagram.

Thermodynamic calculations based on the cycle shown in *Figure 1.*

Enthalpy at state point 1 = 3442.6 kJ kg^{-1}

$$s_2 = s_{f2} + x_2 s_{fg2}$$

$$0.649 + x_2\, 7.5 = 7.06 \text{ .... (steam tables)}$$

Dryness fraction after isentropic expansion, x = 0.86

This is lower than the desired value of 0.88

$$\text{Also, } h_2 = h_{f2} + x_2 h_{g2} = 193 + (0.86 \times 2392) = 2225 \text{ kJ kg}^{-1}$$

$$\text{Turbine work output} = -W_{12} = h_1 - h_2 = 3443 - 2225 = 1218 \text{ kJ kg}^{-1}$$

Feed pump work is indicated by the vertical line from state point 3 to 4.

$$h_3 = h_f = 193 \text{ kJ kg}^{-1}$$

$$\text{Work done by the feed pump} = v_f (p_4 - p_3) = 0.1 \times (42-0.1)$$

where, v_f is the specific volume of saturated water at 0.1 bar(abs) pressure
= 4.19 kJ kg^{-1} (usually ignored)

$$\text{Rankine efficiency} = \frac{(h_1 - h_2)}{(h_1 - h_3)} \text{ (ignoring work done by the pump)}$$

$$= \frac{(3443 - 2225)}{(3443 - 193)}$$

$$= \frac{1218}{3250} = 37.5\ \%$$

$$\text{Specific steam consumption (ssc)} = \frac{1}{(h_1 - h_2)} = \frac{1}{1218} = 0.000821 \text{ kg kWs}^{-1}$$

$$= 3 \text{ kg kWhr}^{-1}$$

$$\text{Condenser heat load} = \text{ssc} \times (h_2 - h_3) = 0.000821 \times (2225 - 193)$$

$$\text{Condenser heat load} = 1.61 \text{ kW kW}^{-1} \text{ power output}$$

Condensate Cooling

Condensate cooling is expected to be a major problem in most mills as most of the mills rely on nearby streams that may dry up during prolonged draught. Thecommon options are:

- surface condensers using circulating water at the rate of 100 t^{-1} of steam can be used for condensate cooling. Hence for a 20 t hr^{-1} boiler, cooling water needed will be in the region of 2000 t hr^{-1} (33.3 t min^{-1} for a temperature rise of 5.5°C). This will require large water storage ponds and cooling towers in the absence of sea water.
- another option also popular is finned tube coolers with large cooling fans as installed in Conaught Bridge power station, Klang. There are many power stations in the world using this system of condenser cooling. However, there is a need to find out the electrical loading.

Boiler Water Treatment

The present simple water treatment system practiced in palm oil mills will not be suitable for boilers steaming at higher pressures. A demineralization plant will have to be set up to ensure purity of boiler water. Additional treated water tanks for feed make-up water also will be needed to ensure constant supply of water to the boiler.

The boiler monitoring equipment also will need reviewing as additional metering for monitoring continuous flue gas analysis, carbon monoxide and oxygen monitoring system, feed water oxygen level monitoring equipment and etc. also need to be incorporated to ensure prolonged boiler life.

DESIRED BOILER FEATURES

The boiler combustion chamber must be designed to handle mostly shredded EFB with an expected moisture content of about 45% after mechanical pressing. The combustion chamber also should cater for opportunity fuels like palm fronds, trunks and other types of biomass. The EFB is high in potash content and contains some hydrogen sulphide (reported to be 2000 ppm) and traces of chlorine as well. As wet shell also is expected to be used as boiler fuel, the ash formed after combustion has to be immediately quenched in water before allowing it to reach its fusion temperature. Therefore, the boiler shall have provision to quench the ash in water and continuously evacuate it. There must also be a receptacle for ash storage and its disposal. The conveyor system must be able to withstand the high furnace temperatures without distortion and any system adopted must be a proven one.

The fuel will need pre-treatment before combustion. Shredding followed by mechanical pressing to squeeze out the moisture uses less energy than drying. Hence, steam drying is not recommended. Steam drying involves high consumption of steam due to the need to evaporate the moisture requiring latent heat extracted from the steam generated. The pressing operation will generate large quantities of effluent, out of which some oil can be recovered but the problem of dealing with effluent still need to be addressed. The whole fuel storage, handling and treatment systems have to be fully automated as the power plant has to operate with minimum manpower to reduce operating cost.

The flue gasses currently discharged into atmosphere is far from satisfactory from environmental point of view. Electrostatic precipitators or venturi wet scrubbers or similar equipment to trap solid particulates must be installed in the power plant.

Main Equipment List

This is not an exhaustive list but covers the main components

No.	Equipment	Remarks
1	A water tube boiler 20 t hr^{-1}, 42 bar pressure c/w all axillaries and essential recorders for monitoring.	Higher temperature preferred to reduce the dryness fraction of exhaust steam from 0.82 to 0.9.
2	An economizer to heat up feed water to 100°C.	To recover the waste heat in flue gas and improve thermal efficiency.
3	Air pre-heater to ensure a stack temperature not exceeding 180°C.	To recover the waste heat in flue gas and improve thermal efficiency.
4	Demineralization plant with water storage tanks.	Water treatment becomes critical at high boiler pressures.
5	Flue gas dust collector system. Electrostatic precipitator or venturi wet scrubber.	Evaluate the best option considering environmental issues.
6	Fuel shedder.	Check on power consumption. Total auxiliary loading should not exceed 12% of generated power.
7	EFB press.	Check on power consumption. Total auxiliary loading should not exceed 12% of generated power.
8	Effluent disposal system (mill to handle?).	To channel to the mill effluent after oil recovery.
9	10 MW condensing type turbo-generator. Inlet condition 42 bar-a, exhausts at 0.1 bar (abs). Alternator to generate at 11 KV.	Provided higher capacity for flexibility. A 11 KV alternator is recommended as it can do away with the transformer.
10	A finned tube heat exchanger or a surface condenser c/w a cooling tower – optional.	Preference for surface condenser subject to water availability.
11	Substations transmission lines and associated equipment.	This is left to TNB distribution.
12	Cooling towers and any other equipment.	May be required if the cooling water is insufficient for condenser.
13	Fuel storage and handling system.	This must be done with much care. In most places, the project fails due to lack of consideration given to this.