INTERNATIONAL JOURNAL of OIL PALM

Volume 2, Number 1, January 2019
Page 24-32
DOI: https://doi.org/10.35876/ijop.v2i1.26

ISSN: 2599-3496 print
ISSN: 2614-2376 online

Valuation of Waste Oil Palm Biomass for Energy in Palm Oil Mill in Indonesia

Armansyah Halomoan Tambunan*

Bogor Agricultural University, Bogor 16680, Indonesia.

ABSTRACT

Valuation of biomass and its waste is indispensable for sustainable development of bioenergy in Indonesia. The objective of this research is to estimate the value of biomass, mainly from oil palm waste, for supporting bioenergy development in Indonesia. The research was applying thermodynamic theory to reinterpret the economic valuation by exergonomic analysis on biomass conversion to electricity. The results revealed that exergonomic value of electricity generated from oil palm fiber was 5 cents USD kWh^{-1}, while the steam was 0.46 cents US kWh^{-1}, under the assumption of zero biomass value. When the value of electricity was at its production base cost, the biomass (i.e. oil palm fiber) could be valuated to Rp 296.57 per kWh of its exergy content, or Rp 1 764.73 kg^{-1} of the biomass. The real price of shell in the field was Rp 700 kg-1. The results show that either the oil palm fiber is undervalued or the production cost of electricity generated from the fiber could be lower.

Keywords: bioenergy, characterization, exergonomic analysis, utilization

INTRODUCTION

Intensive development of modern bioenergy is predicted to escalate its utilization even more, and consequently increases the requirement for biomass supply. However, biomass supply is not unlimited, especially if environmental supporting load and other competitive use is put into account. Accordingly, ingenious way of biomass supply-demand management, and consideration is necessary in order to assure its sustainability. Assessment on the availability of the biomass as energy feedstock is important in revealing its present status and in seeking a strategic plan for sustainable supply of future bioenergy demand in regards to technical potential that can be exploited. Natural conditions that favor the growth of biomass determine the theoretical potential, but further analysis and consideration is required in order to take measures on environmental conservation and competition with food and other uses. Moreover, the development of bioenergy is also expected to be a strategic instrument for poverty eradication and rural development in countries where the supply is abundant (PP No.47, 2014). This is especially more effective for the utilization of scattered (distributed) biomass such as agricultural

*Corresponding author:
Department of Mechanical and Biosystem Engineering, Faculty of Agricultural Engineering and Technology
Bogor Agricultural University, Bogor 16680, Indonesia.
Email: ahtambun@apps.ipb.ac.id

wastes as opposed to the concentrated biomass produced by large scale plantation. Abundance supply of biomass in Indonesia is by no means considered as low economic value. Valuation of the biomass is indispensable to the development of the resource itself, the conversion technology to bioenergy and the policy should be implemented for its sustainable development.

Bioenergy conversion industry is closely related to thermal systems, which typically experience significant work and/or heat interactions with their surroundings. The design of thermal system involves the application of thermodynamics principles, fluid mechanics and heat transfer, as well as material science, manufacturing and mechanical design. In Energy-based thermodynamic analysis, the principle of conservation of energy is applied and used to assess the performance and efficiency of energy systems and processes. However, it can only identifies energy transfers to the environment as thermodynamic inefficiencies, but fails to identify any inefficiencies in an adiabatic process and misleads the engineers by considering the heat rejection to the environment, dictated by the second-law of thermodynamics (e.g., Carnot process), as an inefficiency. Energy-based thermodynamic evaluations do not provide information on the degradation of energy during the processes and do not quantify the energy and material streams, which are flowing through the systems.

New paradigm in the design of thermal system is by the application of the first and second law of thermodynamics, called as exergy analysis (Tambunan *et al.* 2010). Exergy analysis is performed for identification of exergy streams, which can be used as a rational basis for assigning and yielding in exergy efficiency. Exergy analysis can also be used to calculate the monetary cost by inefficiency of exergy utilization. Exergy represents the commodity of real thermodynamic value; therefore, exergy is considered as the only rational basis for assigning monetary values (exergy costing principle). Exergy analysis accurately identifies the margin available to design more efficient energy systems by reducing inefficiencies (Saving Money). Exergoconomics analysis is an exergy based method that identifies and calculates the location, magnitude, causes and costs of thermodynamic inefficiencies in an energy conversion system and link it to the conventional economic analysis. Exergonomic analysis is considered as a robust analytical tool valuate the utilization of biomass for energy generation.

The objective of this study is to valuate the waste biomass, especially fiber as oil palm waste, to be converted to electricity and steam by using exergonomic analysis.

MATERIALS AND METHODS

Exergonomic analysis was performed by using an exergonomic cost balance for each unit of process, which can be constructed from the flow diagram of the industrial process (Valero *et al.* 1986; Lozano & Valero 1993), as shown in Figure 1. The exergonomic cost balance of unit A is shown in equation 1, where ε is the exergy rate (kW), c is cost per unit of exergy (Rp kWh^{-1}), Z accounts for the economic cost rate associated with owning and operating the boiler (Rp h^{-1}). Subscript F, m, L stand for fuel, mass and loss, respectively, while subscript 1, 2 and 3 stand for the respective states. Accordingly, equation for exergonomic cost balance can be constructed as in equations 1 and 2 for unit A and B, respectively.

$$c_{F1}\dot{\varepsilon}_{F1} + c_{m1}\dot{\varepsilon}_{m1} + \dot{Z}_A = c_{m2}\dot{\varepsilon}_{m2} + c_{L1}\dot{\varepsilon}_{D1} \quad [1]$$

$$c_{F2}\dot{\varepsilon}_{F2} + c_{m2}\dot{\varepsilon}_{m2} + \dot{Z}_B = c_{m3}\dot{\varepsilon}_{m3} + c_{F3}\dot{\varepsilon}_{F3} \quad [2]$$

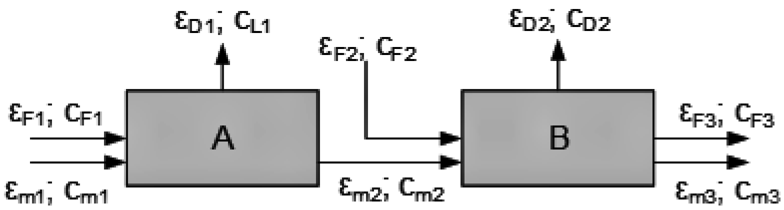

Figure 1 Schematic flow diagram of industrial process for exergonomic analysis.

The economic cost rate (Z) is obtained from standard economic analysis for process components including investment, operation, and maintenance for each of the unit process within the flow diagram of the biomass conversion to energy. Exergy analysis on the heat recirculation process was performed using the governing equations shown in equation 3.

$$\frac{d\varepsilon}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W} - p_0\frac{dV}{dt}\right) + \sum_i \dot{m}\varepsilon_i - \sum_e \dot{m}\varepsilon_e - \dot{\varepsilon}_d \quad [3]$$

Where $\frac{d\varepsilon}{dt}$ is rate of exergy change, $\sum_j \left(1 - \frac{T_0}{T_j}\right) Q_j$ is the exergy transfer associated with the heat transfer, and $\left(W - p_0\frac{dV}{dt}\right)$ is associated with mechanical work, $\sum \dot{m}\varepsilon$ is associated with stream of matter at the inlet (subscript i) and outlet (subscript e), and $\dot{\varepsilon}_d$ is rate of exergy destruction. For a steady state process, the $\frac{d\varepsilon}{dt}$ =0 and $\frac{dV}{dt}$ =0, which lead to equation 4.

$$\dot{\varepsilon}_d = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \dot{W} + \sum_i \dot{m}\varepsilon_i - \sum_e \dot{m}\varepsilon_e \quad [4]$$

RESULTS AND DISCUSSION

Energy and Exergy Analysis

Energy and exergy analysis are normally performed in terms of energy and exergy balance, respectively. The system to be analyzed is biomass conversion to electricity and process steam, as typically used in Palm Oil Mills. The analysis was conducted at each unit of the system, as shown in Figure 2. Combuster, super-heater and economizer are normally combined in one unit as boiler. Other units to be analyzed are turbine and generator. The input to the system are biomass, feed water and air, while the output are electricity from generator and process steam from turbine. Only biomass is regarded to have exergy content, while exergy content of feed water and air is regarded as negligible.

Energy content of fuel, including biomass, can be represented by its heating value. Heating value is the amount of heat can be obtained if the fuel perfectly combusted to carbon dioxide and water. The heating value can be presented as higher heating value (HHV) and lower heating value (LHV), which is differ by the amount of vaporization heat of water resulted from the combustion reaction. LHV does not account the vaporization heat so it is remain in vapor state, while HHV account the vaporization heat after the water condensed to liquid state. The HHV and LHV of biomass can be predicted from its elemental components by using equation 5 and 6.

$$HHV = 0.35C + 1.18H + 0.10S - 0.02N - 0.10O - 0.02A \quad [5]$$

$$LHV = HHV\left(\frac{m_{fibre}}{m_{fibre} + m_{ash}}\right) \quad [6]$$

Chemical exergy (ε, in kJ g^{-1}) of biomass for dry basis can be calculated based on its ultimate analysis using equation 7. Chemical exergy is the work that can be obtained from the fuel when it is brought to equilibrium with the surroundings through a reversible process. Thus this is the maximum work from the fuel.

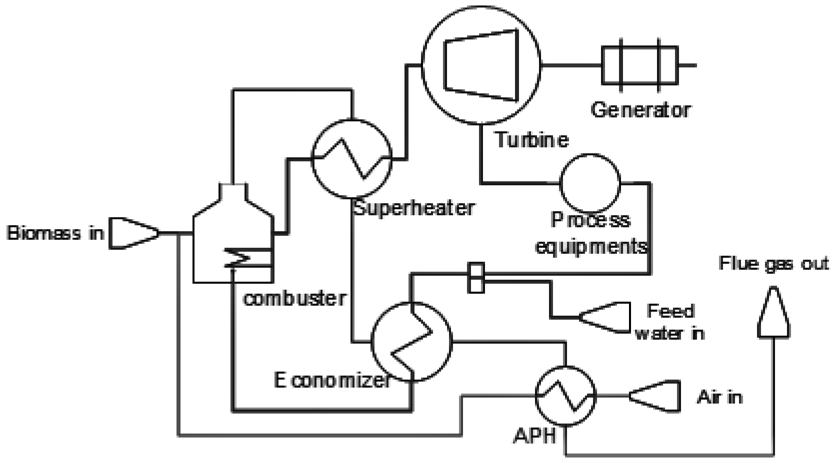

Figure 2 Schematic chart of typical energy conversion process in palm oil mill.

The value is often close to the heating value. When energy in fuels is quantified, it is (with some special exceptions) the lower heating value. For moist fuels, it is the effective heating value (lower heating value of the moist fuel).

$$\varepsilon_{db} = 1812.5 + 295.606C + 587.354H + 17.506O + 17.735N + 95.61S - 31.8A \quad [7]$$

Where C, H, O, N, S and A is content of carbon, hydrogen, oxygen, nitrogen, sulfur and ash, respectively (%wt). Another way to calculate chemical exergy of biomass is by using the relation of the exergy to lower heating value as shown in equation 8, 9 and 10.

$$\phi_{db} = \frac{\varepsilon_{db}}{LHV_{db}} \quad [8]$$

For biomass with O/C within 0.667-2.667, the ratio of exergy to lower heating value for dry matter is expressed as:

$$\phi_{db} = \frac{1.0438 + 0.1882\,{}^{H}/_{C} - 0.2509\left(1 + 0.07256\,{}^{H}/_{C}\right) + 0.0383\,{}^{N}/_{C}}{1 - 0.3035\,{}^{O}/_{C}} \quad [9]$$

While for moist fuel, such as biomass, it is given by equation [10] with ω is moisture content (-) and h_{fg} is latent heat of evaporation of water (kJ kg^{-1}).

$$\phi = \frac{\varepsilon_{moist}}{h_{eff}} = \frac{(1-\omega)\varepsilon_{dm}}{(1-\omega)LHV_{dm} - \omega h_{fg}} = \left(1 - \frac{\omega}{1-\omega}\frac{h_{fg}}{LHV_{dm}}\right)^{-1}\phi_{dry} \quad [10]$$

Value of HHV, LHV and exergy as calculated with those equation, using the elemental data provided by Song *et al.* (2012). It was found that chemical exergy of biomass calculated by using equation 7 match very well with that calculated by using equation 10. Relationship between LHV and chemical exergy for biomass is shown in Figure 3. It was found that LHV give good linear correlation to chemical exergy of biomass. It means that the relationship as shown by linear equation in the figure can be used to predict chemical exergy in case the ultimate analysis of the biomass is not available.

There are two main sources of irreversibility in the boiler: (1) the irreversible heat transfer occurring between the hot combustion gases and the working fluid of the vapor power cycle flowing through the boiler tubes, and (2) the combustion process itself. The energy and exergy of steam entering and exiting the boiler can be calculated by using equation of heat and exergy balance as shown in equation 11. Thermodynamic properties of the steam at the operating condition of the boiler are obtained from thermodynamic diagram.

Energy balance at the boiler:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + (m_{sb,i}h_{sb,i} - m_{sb,o}h_{sb,o}) \quad [11]$$

For steady state condition, the energy derivation is zero and there is no work done by or to the boiler. The equation, then, can be simplified to equation 12.

$$\dot{m}_{sb,i}h_{sb,i} + \dot{Q} = m_{sb,o}h_{sb,o} \quad [12]$$

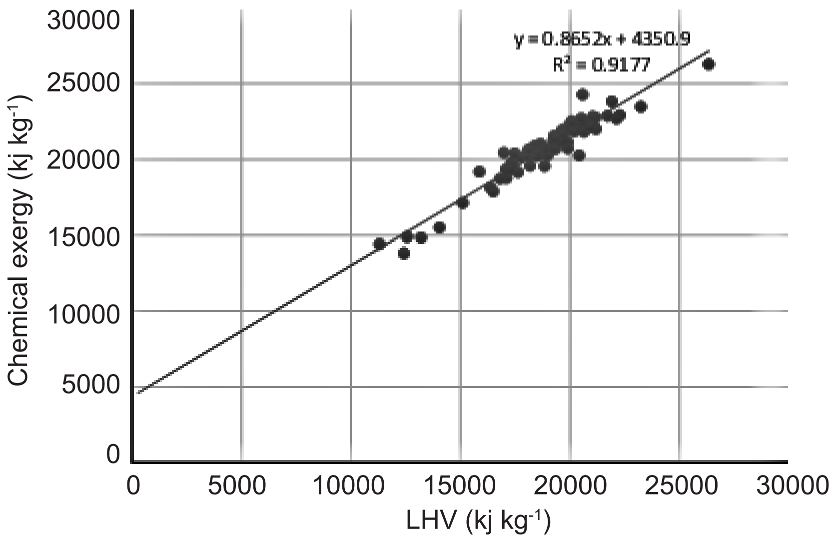

Figure 3 Relationship between HHV and chemical exergy of various biomass.

Entropy balance:

$$m_{sb,i}s_{sb,i} + \frac{Q}{T} = m_{sb,o}s_{sb,o} + \sigma_b \quad [13]$$

Exergy balance:

$$m_{sb,i}(h_{sb,i} - T_0 s_{sb,i}) + \frac{T_0}{T}Q = m_{sb,o}(h_{sb,o} - T_0 s_{sb,o}) + T_0\sigma_b \quad [14]$$

Here, m is steam flow rate (kg s^{-1}), h is enthalpy (kJ kg^{-1}), s is entropy (kJ kg.K^{-1}), Q is heat rate entering the boiler (kJs), T is operating temperature of the boiler (K), T_o is reference temperature (K), while subscript *sb* for boiler steam, *i* for inlet and *o* for outlet.

A steam turbine is a device that extracts thermal energy from pressurized steam and uses it to do mechanical work on a rotating output shaft. The mechanical work then can be used to drive an electrical generator and produce electricity. The energy, entropy and exergy balance of a steam turbine can be derived as the following equations, and as it is for boiler, the thermodynamic property can be obtained from the T-s diagram.

Energy balance at the turbine:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + (m_{st,i}h_{st,i} - m_{st,o}h_{st,o}) \quad [15]$$

For steady state condition, the energy derivation is zero and heat transfer from and to the turbine can be neglected the equation can be simplified to equation 16.

$$\dot{m}_{st,i}h_{st,i} = m_{sb,o}h_{sb,o} + W \quad [16]$$

Entropy balance:

$$m_{st,i}s_{st,i} = m_{st,o}s_{st,o} + \sigma_t \quad [17]$$

Exergy balance:

$$m_{st,i}(h_{st,i} - T_0 s_{st,i}) = m_{st,o}(h_{st,o} - T_0 s_{st,o}) + T_0\sigma_t \quad [18]$$

Energy analysis of a thermal system can be performed using the temperature-heat content (T-Q) diagram. T-Q diagram is widely applied to the thermodynamic analysis and synthesis of process systems. The T-Q diagram is an alternative technique that gives useful insights into the temperature-driving force for heat transfer between the streams. T-Q diagram for boiler and turbine as plotted using a set of data obtained from energy station of a palm oil plant is shown in Figure 4 schematically. The T-Q diagram is based on the relationship between the amount of heat content of the steam to the temperature of the stream.

Exergy of a thermal process can be expressed as in equation 19. Based on the equation, analogic to the T-Q diagram can be constructed by plotting Q and ($1-T_o T^{-1}$). Since the multiplication of both parameters is the exergy transfer done during the unit process, the diagram can be named as Exergy Diagram. The heat

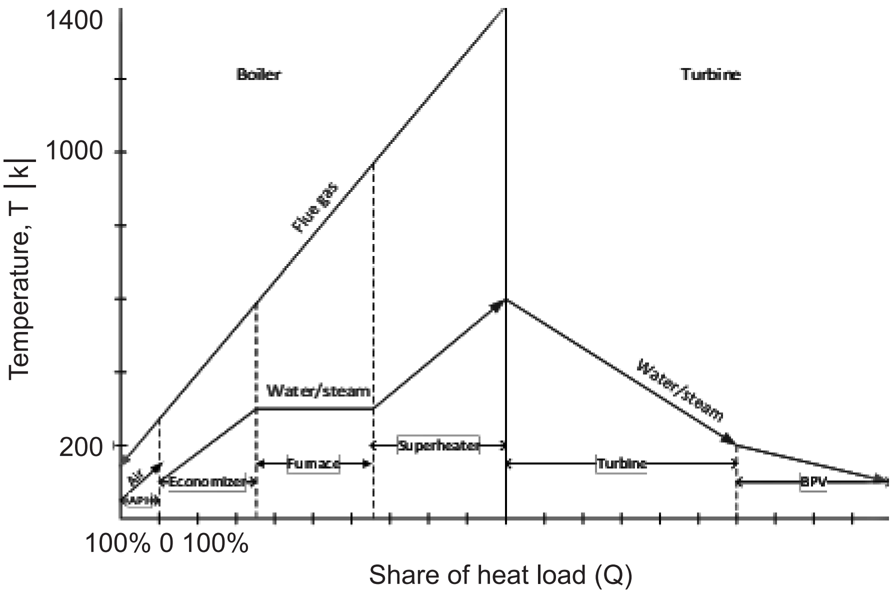

Figure 4 Temperature vs heat load (T-Q) diagram of boiler-turbine system.

content (Q) in the exergy diagram can be expressed in share percentage, or in nominal amount. Exergy diagram for the total system, including turbine and generator, as calculated from data obtained from a plant oil plant is given in Figure 5.

$$\varepsilon = Q\left(1 - \frac{T_0}{T}\right) \quad [19]$$

Exergonomic Analysis of Electricity Production from Palm Waste

The exergonomic analysis was performed by combining the exergy analysis and economic analysis at each of the unit process. The chain of the unit process for converting waste biomass to steam and electricity along with the exergy and exergy cost input-output, in simplified mode, is shown in Figure 6. The energy conversion system at palm oil plant is integrated in a larger system which also utilize the steam generated in the boiler for processing the oil palm to crude palm oil (CPO). The processing steam is obtained after the turbine at lower steam temperature and pressure.

Based on the schematic diagram, the equations for exergonomic analysis at each of the unit process can be developed as shown in equations 20-23.

$$c_{b1}\dot{\varepsilon}_{b1} + \dot{Z}_D = c_{b2}\dot{\varepsilon}_{b2} \quad [20]$$

$$c_{b2}\dot{\varepsilon}_{b2} + c_a\dot{\varepsilon}_a + c_w\dot{\varepsilon}_w + \dot{Z}_B = c_{s1}\dot{\varepsilon}_{s1} \quad [21]$$

$$c_{s1}\dot{\varepsilon}_{s1} + \dot{Z}_T = c_{s2}\dot{\varepsilon}_{s2} + c_m W_m \quad [22]$$

$$c_m W_m + \dot{Z}_M = c_e W_e \quad [23]$$

Taking the efficiency of digester, boiler, turbine and motor as *ηD, ηB, ηT* and *ηM*, respectively, where $\eta_D = \frac{\dot{\varepsilon}_{b2}}{\dot{\varepsilon}_{b1}}$; $\eta_B = \frac{\dot{\varepsilon}_{s1}}{\dot{\varepsilon}_{b2}}$; $\eta_T = \frac{W_m}{\dot{\varepsilon}_{s1}}$; $\eta_M = \frac{W_e}{W_m}$; then

$$\dot{\varepsilon}_{b2} = \eta_D\dot{\varepsilon}_{b1} \quad [24]$$

$$\dot{\varepsilon}_{s1} = \eta_B\dot{\varepsilon}_{b2} = \eta_B\eta_D\dot{\varepsilon}_{b1} \quad [25]$$

$$\dot{\varepsilon}_{s2} = (1-\eta_T)\dot{\varepsilon}_{s1} = (1-\eta_T)\eta_B\eta_D\dot{\varepsilon}_{b1} \quad [26]$$

$$W_m = \eta_T\dot{\varepsilon}_{s1} = \eta_T\eta_B\eta_D\dot{\varepsilon}_{b1} \quad [27]$$

$$W_e = \eta_M\dot{\varepsilon}_m = \eta_M\eta_T\eta_B\eta_D\dot{\varepsilon}_{b1} \quad [28]$$

The required ratio of air and feed water can be defined in term of its exergy content as

$\dot{\varepsilon}_a = r_a\dot{\varepsilon}_{b1}$; and $\dot{\varepsilon}_w = r_w\dot{\varepsilon}_{b1}$ [29]

Equation 24-26 are inserted to equation 20-23 and rewritten in form of incidence matrix to be solved for vector c. The required input data for solving the matrix was obtained from a palm oil plant as shown in Table 1. Inserting the data into the matrix according to the rule required by

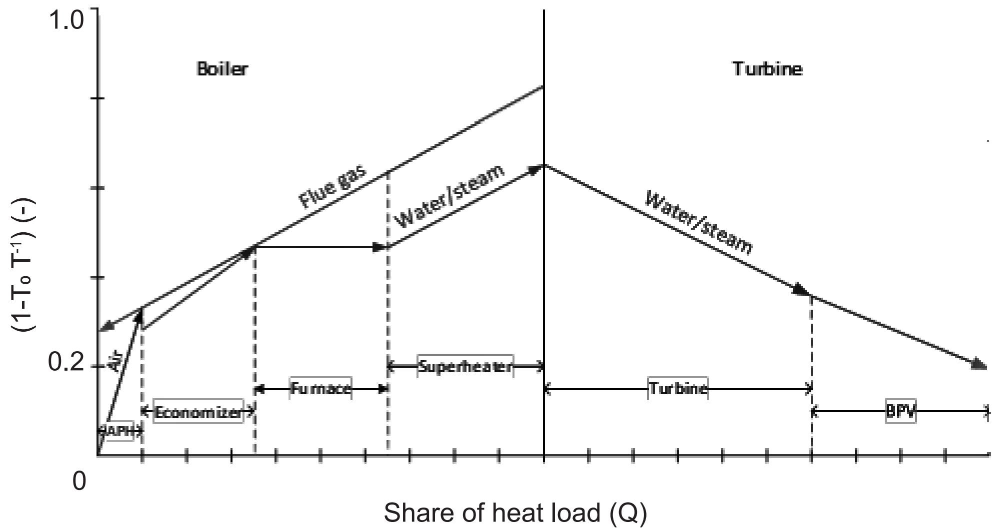

Figure 5 Exergy diagram of boiler-turbine system.

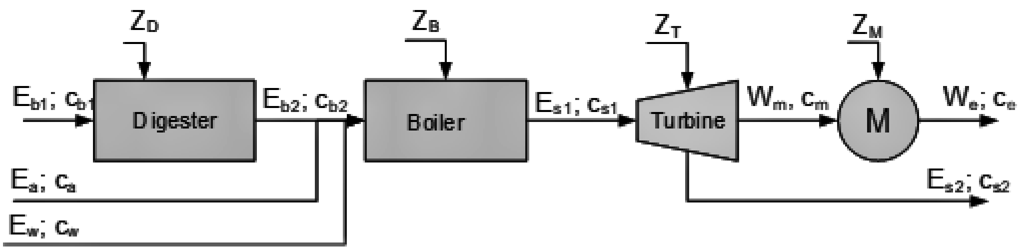

Figure 6 Simplified diagram of oil palm waste utilization for energy.

Table 1 Input data for exergonomic analysis

	Digester	Boiler	Turbine	Motor	BPV	Output	Unit
Exergy in	E-b1	E-b1	E-s1	E-m	E-s2	E-e	
	20293	20293	5166	625	3433.41	500	kW
Efficiency	Eta-D	Eta-B	Eta-T	Eta-M	ra	rw	
	1.00	0.25	0.12	0.80	0.01	0.1	
Economy	Z_D	Z_B	Z_T	Z_M			
	0.0000	0.0012	0.00003	0.00006			$ kWh^{-1}
CAPEX	0	980000	85000	107000			$
Life time	30	30	30	30			years
Salvation	10	10	10	10			%Cap
Capacity			25000				kW
OPEX	10	15	2.5	5			%Cap/y
Operation hours	7500	7500	7500	7500			h/y

the above equations gave the incidence matrix, vector c and vector Z. The tabel was constructed by assuming that plant uses fiber as feedstock to the boiler, and the value of the fiber as waste biomass was ignored. The results show that the value of electricity (c_e) produced from waste fiber of oil palm is 5 cents dollar per kWh, while the value of the steam (c_{s1}) was 0.46 cents dollar per kWh. These results needs to be verified by comparing the input data with those of other palm

Table 2 Exergonomic cost of biomass used as energy source in palm oil plant

Component				Biomass	Boiler	Turbine	Generator	Back-pressure	Unit
Exergy rate	in	fiber		9768.84					kW
		shell		10524.6					kW
		steam		342.34	20635.78	5156.42	625.00	4531.42	kW
	out	biomass		20293.44					kW
		steam		342.34	5156.42	4058.41		3860.06	kW
		electricity					500.00		kW
	dest				11810.83	1081.69	0.00	74.78	kW
	loss				3389.20	16.32	125.00	254.24	kW
Working time			18	18	18	15	15	15	h
Exergy				365281.92	92815.56	60876.15	7500.00	57900.90	kWh
				1315014912	334136016	219154140	27000000	208443240	kJ
Z			1768148.15						Rp h^{-1}
Exergonomic cost				296.57			1852.00	463.00	Rp kWh^{-1}

oil plants and standard price of each unit process.

Table 2 shows the exergonomic cost of biomass (i.e. oil palm fiber and shell) as calculated using those equations. The cost is Rp 296.57 per kWh of the biomass exergy, or Rp 1 067.65 per MJ of the exergy contained in the biomass. Thereby, the price of the biomass should be Rp 1 764.73 kg^{-1}. The real price of shell in the field was found to be Rp 700 kg^{-1}, which is undervalued. This situation could be caused by low demand of the biomass. Technology of biomass conversion to energy could increase the value up to its exergonomic value.

CONCLUSIONS

The results of exergonomic analysis show that under the assumption of zero biomass value, the value of electricity produced from waste fiber of oil palm was 5 cents dollar per kWh, while the value of the steam was 0.46 cents dollar per kWh. When the value of electricity is fixed as its standard production cost, the exergonomic cost of biomass (i.e. oil palm fiber and shell) was Rp 296.57 per kWh of the biomass exergy, or Rp 1 764.73 kg^{-1} of the biomass. The results show that either the oil palm fiber is undervalued or the production cost of electricity generated from the fiber could be lower.

ACKNOWLEDGEMENT

This research was funded by Ministry of Research Technology and Higher Education of Indonesia under the scheme of International Join Research fiscal year 2015-2017.

REFERENCES

Lozano MA, Valero A. 1993. Theory of the exergetic cost. Energy. 18(9):939-960.

PP No.47 2014. Presidential Regulation No.47/2014 regarding Indonesian national energy policy, Government of Indonesia, Jakarta.

Song GL, Shen J, Xiao. 2011. Estimating specific chemical exergy of biomass from basic analysis data. Ind Eng Chem Res. 50:9758-9766.

Tambunan AH, Manalu LP, Abdullah K. 2010. Exergy analysis on simultaneous charging and discharging of solar thermal storage for drying applications. Dry Technol. 28:1007-1012.

Valero A, Lozano MA, Munoz M. A General Theory of Exergy Savings. I. On the Exergetic Cost. Book No. H0341C. New York (US):The American Society of Mechanical Engineers.