Potential Co-Generation of Electrical Energy from Mill Waste: A Case Study of the Malaysian Furniture Manufacturing Industry

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Furniture manufacturing in Malaysia is an established industry driven primarily by the availability of raw materials and labor. However, the industry suffers from the low-recovery rate of its materials, as it produces a substantial amount of waste during the manufacturing process. Although smaller waste fragments, or off-cuts, are recovered for other purposes, the splinters, shavings, and coarse dust have little economic value and are often discarded. Because wood is a well-established source of bioenergy, this study investigated the potential use of mill waste from the furniture-manufacturing industry for electrical energy generation. Waste from the rubberwood, bamboo, and rattan furniture industries was evaluated for its potential electrical energy generation, and the amount was compared with the electrical energy that was consumed by the furniture industry. The study also compared the emission of greenhouse gases from the combustion of these waste materials against fossil fuels used to generate electricity to assess its potential in terms of the environmental benefits. In conclusion, such mill waste could be utilized as substitute for fossil fuel to generate energy in the furniture industry.

Keywords: Mill waste; Furniture industry; Energy; Greenhouse gases; Carbon footprint

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INTRODUCTION

The successful growth of the furniture industry in Malaysia has received all-around praise. Since 1986, a series of government-led Industrial Master Plans (IMPs) have transformed the furniture industry from a cottage-based sector to a multi-billion dollar industry within three decades. As a result, the furniture industry has emerged as one of the fastest growing of the wood products manufacturing sub-sectors of high-volume production capacity (NATIP 2009). The socioeconomic importance of the industry, in the context of workforce employment and foreign exchange earnings, has increased significantly over the years (Ratnasingam *et al.* 2011). According to the Malaysian Furniture Council (2015), the export earnings of this industry was USD $2.1 billion, while providing jobs for approximately 88,000 workers in the year 2014.

The ample availability of raw material has enabled the rapid expansion of the furniture industry in Malaysia (NATIP 2009). The increasing use of rubberwood (*Hevea brasiliensis*) as the primary raw material for furniture manufacturing, due to the reducing supply of wood from the natural forest, also had a positive impact on the industry (Menon

2000). Furniture made from rubberwood is widely accepted in the international market for its pleasant appearance, light colour, abundance, good machining properties, low cost, and renewable image (Ratnasingam *et al*. 2015a). Its popularity is shown by its substantial export value; 80% of wooden furniture is made from this material.

There has also been an increasing use of non-wood materials in furniture manufacturing. The National Timber Policy (NATIP 2009) emphasized that bamboo (*Gigantochloa scortechinii*) and rattan (*Calamus manan*) are the two main non-wood materials that are accepted in the furniture industry, due to their high potential for furniture making. Both species are fast-growing, and their supply is replenished quickly after harvesting. An estimation by the Malaysian Furniture Council (2015) notes that almost 35,000 m^3 of these materials were used in furniture manufacturing in 2014.

Although the furniture industry is well established in Malaysia, one major issue is the high amount of waste produced during furniture manufacturing. Waste is normally generated in the forms of machining dust, planer shavings, and smaller fragments, or off-cuts. Generally, the smaller fragments or off-cuts are recovered for other purposes in the mills, but planer shavings and machining dust are often discarded due to their minimal economic value. In mills that have their own boilers, this waste is used as boiler fuel. Ratnasingam and Scholz (2015) reported that the average recovery in rubberwood, rattan, and bamboo furniture mills was 74%, 78%, and 70%, respectively.

Mill waste is infrequently used as an energy source in Malaysia, although many studies have shown that it is a promising source of biomass energy (Chuah *et al.* 2006; Muis *et al.* 2010; Mekhilef *et al.* 2011; Shafie *et al.* 2012; Mi and Han 2014; Noridah *et al.* 2014; Ratnasingam *et al.* 2015a). Furthermore, wood residue is a viable option for electricity generation (Muis *et al.* 2010). Hence, using mill waste as a renewable energy source is an attractive solution to reducing the dependency on fossil fuels and mitigating climate change (Chuah *et al.* 2006; Gan and Smith 2006; Ong *et al.* 2011; Shafie *et al.* 2012; Ratnasingam *et al.* 2015a).

Furniture manufacturers, especially the larger mills, could use the waste as an alternative source for electrical energy production. This study investigates the potential electrical energy that could be generated from rubberwood, bamboo, and rattan furniture mill waste. In this context, the objectives were: (1) to assess the amount of waste produced in these industries; (2) to compare the potential electrical energy generation between mill waste and fossil fuels; and (3) to compare the emission of greenhouse gases (GHGs) expressed as a carbon dioxide equivalent (CO_2-eq) during the combustion of mill waste and fossil fuels.

EXPERIMENTAL

Materials

Three types of furniture raw materials were obtained from local suppliers in Peninsular Malaysia. Solid rubberwood (*H. brasiliensis*) was the primary raw material, while the non-wood materials were bamboo (*G. scortechinii*) and rattan (*C. manan*).

Evaluation of mill waste production

The amount of mill waste produced was based on the amount of raw materials used by the larger furniture manufacturing mills in the country. In 2014, there were 3,844 furniture-manufacturing establishments, but only a total of 323 mills were classified as 'large' mills. According to the Malaysian Furniture Council (MFC), furniture-manufacturing mills with more than 100 employees and an annual turnover in excess of USD $10 million are categorized as large mills. The identities of these large furniture-manufacturing mills were provided by the MFC. The large furniture mills accounted for almost 85% of the total furniture production in the country (MFC 2015), and from this total, 249 were wooden furniture mills, 46 were rattan furniture mills, and 28 were bamboo furniture mills.

Methods

The mill waste data were compiled and enumerated from the production records that are submitted by the mills to the MFC quarterly. Two sets of data were compiled throughout the study period of 2014, *i.e.*, the total mill waste produced and the total electrical energy consumed by the mill. The data was compiled on a monthly basis and also differentiated for the various workstations or machining centers at the mills, which include machines such as cross-cut, surface planer, moulder, narrow band-saw, router, borer/drill, mortiser, tenoner, and sander/grinder.

Quantification of mill waste

The mill waste produced at each workstation at the mills was either planer shavings or machining dust (ranging from 0.5 mm to 5.0 mm in size). The volume of the waste produced and extracted from the secondary data provided by the MFC was verified through actual field measurements. The volume of waste was calculated from mill waste collected in waste bags at 25 furniture mills over a period of one month. A comparison of the two data sets showed an average variation of 5.5%, which is acceptable for large-scale manufacturing industries (Ratnasingam 2015).

The volume of mill waste was used to calculate the potential electrical energy that could be generated. According to Noridah *et al.* (2014), the energy content of biomass is usually reported in dry biomass. The first step was to determine the mass value of the mill waste through the known densities of the materials, which are 540 kg/m^3 (Ratnasingam *et al.* 2009), 710 kg/m^3 (Ratnasingam and Scholz 2015), and 690 kg/m^3 (Ratnasingam and Scholz 2015) for rubberwood, bamboo, and rattan, respectively. Once the oven-dry weight of the mill waste was determined, the potential energy value of the mill waste was estimated using a calorific value of 18.41 MJ/kg (Chuah *et al.* 2006).

The energy value of the mill waste was then converted into total potential electrical energy by multiplying by the average energy efficiency factor. Generally, the energy efficiency factor differs based on the technology used during the conversion process. In this case, the conversion process was direct combustion, which has an energy efficiency factor of 0.19 to 0.26 (Shafie *et al.* 2012). In this study, the average value of 0.225 was applied. The potential electrical energy from rubberwood, bamboo, and rattan furniture mill waste was then calculated by Eq. 1, as provided by Gan and Smith (2006),

$$E = D \times V \times CV \times \eta \tag{1}$$

where E is the potential electrical energy from mill waste (MJ), D is the density of mill waste (kg/m^3), V is the volume of mill waste (m^3), CV is the calorific value (MJ/kg), and η is the efficiency of power conversion from biomass to electricity.

Assessment of electrical energy consumption

The second part of the study determined the electrical energy used during the furniture manufacturing process, in which the data was collected using a Watt-meter (Crystal Instrumentation P-04, Taiwan), attached to the drive-motors of every workstation at 25 furniture mills over a period of one month. The average electrical energy consumed at every workstation was then calculated based on Eq. 2, as provided by Devaru *et al.* (2014),

$$EC = \frac{\sqrt{3} \times V \times I \times cosine\ (\emptyset) \times number\ of\ hours}{1000} \tag{2}$$

where *EC* is the electricity consumption (kWh), *V* is the average voltage (voltage), *I* is the average amperage (amperage), and cosine (*Φ*) is the power factor.

Environmental Assessment

Next, the emission of GHGs was enumerated and translated into a carbon footprint, expressed in CO_2-eq.

Assessment of GHGs emission from machining dust

CO_2, CH_4, and N_2O emissions from the wood, bamboo, and rattan furniture mill waste were calculated by Eq. 3. The emission factors of CO_2, CH_4, and N_2O were based on data from International Panel of Climate Change (IPCC) (2006), as shown in Table 1,

$$GHGs = E \times EF \tag{3}$$

where *GHGs* is the emission of CO_2, CH_4, and N_2O (kg), *E* is the potential electrical energy (TJ), and *EF* is the emission factor of wood waste (kg/TJ).

Table 1. Emission Factors for Wood, Bamboo, and Rattan Waste Combustion

GHG	Wood Waste (kg/TJ)
CO_2	112 000
CH_4	30
N_2O	4

Assessment of GHGs emission from fossil fuels

Gas emissions from fossil fuels were calculated as previously described (Saidur *et al.* 2007) (Eq. 4). The electricity generated by the specific fossil fuel was extracted from 2013 data, as reported by the Malaysia Energy Information Hub (2014). The electricity generated by specific fuels of coal, gas, diesel, oil, hydropower, and others were specified as 37.99%, 50.38%, 1.23%, 1.11%, 8.35%, and 0.93%, respectively. The emission factors associated with CO_2, CH_4, and N_2O released from fossil fuels was based on Ramasamy *et al.* (2015), as listed in Table 2,

$$GHGs = EC \times EGF \times EF_{fuel} \tag{4}$$

where *GHGs* is the emission of CO_2, CH_4, and N_2O (kg), *EC* is the electricity consumption (TJ), *EGF* is the electricity generated by specific fuel (%), and *EF* is the emission factor for several types of fuel (kg/TJ).

Table 2. Emission Factors for Fossil Fuel Combustion

GHG	Coal (kg/TJ)	Petroleum (kg/TJ)	Gas (kg/TJ)	Hydro (kg/TJ)
CO_2	96 100	97 500	56 100	0.0000
CH_4	10	3	1	0.0000
N_2O	1.5	0.6	0.1	0.0000

Assessment of CO_2-eq emission

The calculation of CO_2-eq was derived from Ratnasingam *et al.* (2015b) (Eq. 5). GHGs were converted into CO_2-eq by multiplying with the relevant equivalency factor. The equivalency factors for CO_2, CH_4, and N_2O were 1, 25, and 298, respectively,

$$\mathrm{CO_2eq} = EqF \times GHGs \tag{5}$$

where *EqF* is the equivalency factor and *GHGs* is the emission of CO_2, CH_4, and N_2O (kg).

RESULTS AND DISCUSSION

The findings from this study are presented in three parts: (1) the production of mill waste; (2) an electrical energy assessment; and (3) an environmental assessment.

Production of Mill Waste

The average volume of mill waste produced at the various machining centers in the rubberwood, bamboo, and rattan furniture manufacturing industries are shown in Table 3. The average volume of waste from the rubberwood furniture mills was 85.2 m^3, while the bamboo and rattan furniture mills produced 9.1 m^3 and 8.7 m^3, respectively. Moulding operations produced the highest amount of waste, which was 48.94% of the total waste, while cross-cutting operations contributed 47.25% and 52.87% of the total waste produced in the bamboo and rattan furniture manufacturing industries, respectively.

Table 3. Waste Produced in Furniture Manufacturing Industries

Job Category	Rubberwood (m^3)	Bamboo (m^3)	Rattan (m^3)
Cross-cut	2.6	4.3	4.6
Surface planer	4.6	0.4	0.2
Moulder	41.7	0	0
Narrow band-saw	2.1	0	0
Router	18.3	1.1	0.9
Borer	0.9	0.2	0.1
Mortiser	1.2	0	0
Tenoner	1.4	0	0
Sander	12.4	3.1	2.9
Total	85.2	9.1	8.7

Energy Consumption

The assessment of the energy consumption focused on two aspects: (1) the electrical energy consumed in the rubberwood, bamboo, and rattan furniture industries and (2) the potential electrical energy generated by the direct combustion of mill waste.

Assessment of electrical energy consumption in furniture industry

The average amount of electrical energy consumed to produce 1 m^3 of bamboo furniture and rattan furniture was 81.3 kWh and 78.9 kWh, respectively, compared with 75.1 kWh for 1 m^3 of rubberwood furniture. The proportion of total energy used in the various machining centers is shown in Fig. 1. It is apparent that bamboo furniture manufacturing is the most energy-intensive.

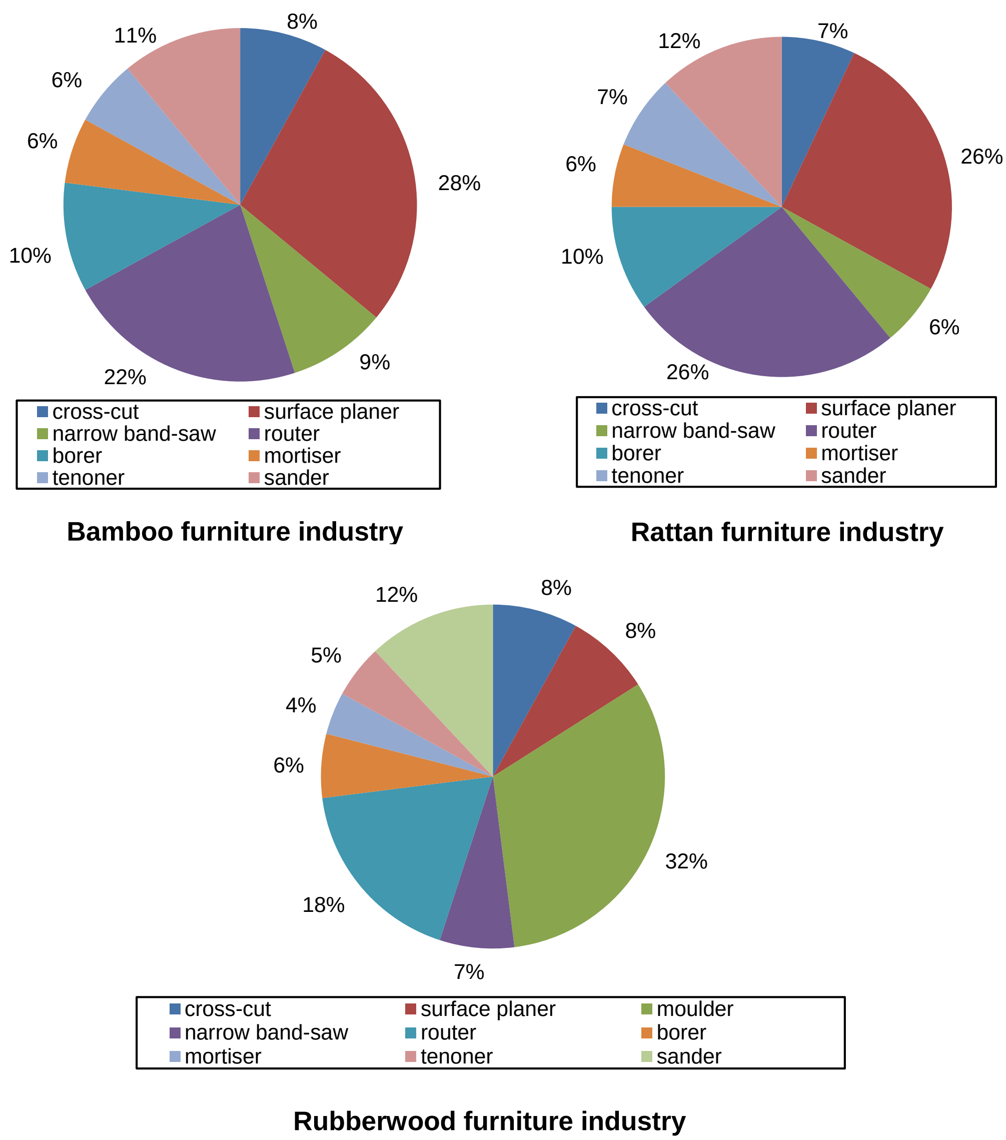

Fig. 1. Proportion of electrical energy used in machining centers in the furniture industry

Potential electrical energy generation from mill waste

Based on the amount of mill waste produced, it is apparent that mill waste is a promising biomass energy source through direct combustion. With an average embodied energy content of 9.94 GJ, 13.07 GJ, and 12.70 GJ for rubberwood, bamboo, and rattan, respectively, the average electrical energy that could be generated from 1 m^3 of mill waste from furniture mills is presented in Fig. 2. Thus, mill waste could significantly reduce the amount of fossil fuels required to produce the electrical energy used by furniture mills.

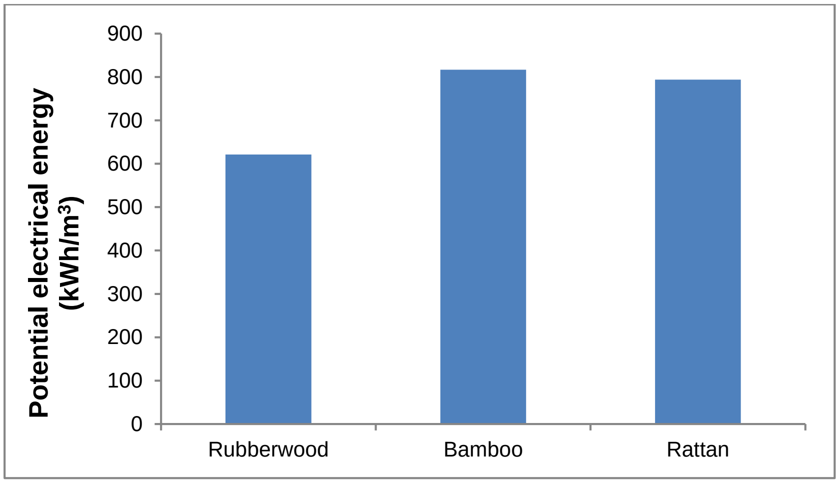

Fig. 2. Potential electrical energy generated from mill waste

Co-generation of energy from mill waste and fossil fuel

The global demand for energy is expected to increase two-fold in the foreseeable future (Tock *et al*. 2010). Economic development and population growth are the two main factors that contribute to the increasing demand for electrical energy. Although Malaysia has an ample supply of fossil fuels, Koh and Hoi (2003) predict that the reserves will only last for the next 40 to 50 years.

Therefore, this study compared the potential generation of electrical energy from the combustion of fossil fuels and mill waste. The comparison was on the basis of 323 large furniture mills. According to the Malaysian Furniture Council (2015), a total of 1.1 million m^3 of rubberwood was used by the furniture industry in 2014, while the amount of bamboo and rattan used was 14,000 m^3 and 21,000 m^3, respectively.

Approximately 25% of the raw material input is produced as waste during furniture manufacturing (Malaysian Furniture Council 2015). If this amount of mill waste is utilized for electrical energy generation, the furniture manufacturing industries will not only be energy sufficient, but the surplus in energy supply may also be fed into the national electricity grid in the country, as shown in Table 4.

Table 4. Potential Energy Supply from Mill Waste

	Electrical Energy Consumption in Furniture Mills (GWh)	Potential Electrical Energy Generation from Mill Waste (GWh)
Rubberwood	61.96	170.87
Bamboo	0.85	2.86
Rattan	1.24	4.17

From an economic viewpoint, the generation of electricity using mill waste could generate about Ringgit Malaysia (RM) 57 million, simply by selling the surplus energy to the national electricity board at a price of RM 0.50 per kWh. However, it must be noted that co-generation of energy is economically viable in the larger mills, which processes more than 100 m^3 of materials a month.

Environmental Emissions

The primary energy sources in Malaysia are fossil fuels. The continued use of fossil fuels will not only exhaust the reserves but also pose negative environmental consequences. Currently, the most important environmental issue is global warming due to the emission of GHGs, particularly the discharge of CO_2 to the environment. The IPCC (2006) predicted that the continuous release of CO_2 in large amounts will increase the average global temperature in the range of 1.4 °C to 5.8 °C from 1990 to 2100. Because wood is carbon-neutral (Ramasamy *et al.* 2015), the wood industries could play an important role in mitigating global warming.

Fossil fuels, namely coal, gas, and petroleum, are combusted in power stations to generate electricity for industrial and domestic use. The fossil fuel-derived electrical energy consumed by the rubberwood, bamboo, and rattan furniture industries discharges greenhouse gases in varying quantities (Table 5). It is apparent that CO_2 emission is the highest, while the rubberwood furniture industry had the highest CO_2 emission levels. The emission levels of CH_4 and N_2O was significantly different compared to the CO_2 emission level. As shown in Table 5, the amount of CH_4 and N_2O emitted was negligible for the rubberwood, bamboo, and rattan furniture industries.

Table 5. Emissions of GHGs from Fossil Fuels derived Electrical Energy (kg)

GHGs	CO_2	CH_4	N_2O
Rubberwood furniture manufacturing	1.50 E+ 01	9.75 E- 04	1.41 E- 04
Bamboo furniture manufacturing	2.05 E- 01	1.34 E- 05	1.94 E- 06
Rattan furniture manufacturing	2.99 E- 01	1.95 E- 05	2.83 E- 06

Similar to fossil fuels, wood stores carbon. One kilogram of wood contains approximately 52.4% of carbon (Wilson 2010), and CO_2 is discharged into the environment when wood or mill waste is combusted. The emission from fossil fuels is classified as an anthropogenic emission, while the emission from biomass is categorized as biogenic carbon. The CO_2 from biomass is carbon neutral, and the CO_2 released from the burning or decomposition of biomass becomes reabsorbed by trees in the forests in the same amount (Ingerson 2009). In this context, it must be emphasized that biogenic CO_2 does not pose any threat to the environment (Sathre and Gustavsson 2011). In other words, the CO_2 emitted from the combustion or decomposition of biomass is recycled and has a global warming potential of 0 (Wilson 2010; Puettmann and Lippke 2012; Muñoz *et al*. 2013; Mi and Han 2014). However, Jäppinen *et al.* (2014) postulated that other GHGs are emitted when a biomass is combusted for electrical generation. The GHGs emitted during the combustion of rubberwood, bamboo, and rattan furniture mill waste to generate electrical energy is presented in Table 6. The emission of CO_2 was the highest in the rubberwood, bamboo, and rattan furniture industries. However, the rubberwood, bamboo, and rattan furniture industries showed markedly different CO_2 emission levels. On the other hand, the emission of CH_4 and N_2O was negligible for the rubberwood, bamboo, and rattan furniture industries.

Table 6. Emissions of GHGs from Mill Waste (kg)

GHGs	CO_2	CH_4	N_2O
Rubberwood furniture manufacturing	6.89 E+ 01	1.85 E- 02	2.46 E- 03
Bamboo furniture manufacturing	1.15 E+ 00	3.09 E- 04	4.12 E- 05
Rattan furniture manufacturing	1.68 E+ 00	4.50 E- 04	6.00 E- 05

The emission of greenhouse gases, expressed in CO_2-eq, as a result of electricity consumption in the rubberwood, bamboo, and rattan furniture manufacturing mills was compared with the potential electricity supply from the combustion of mill waste. As shown in Table 7, the emission of greenhouse gases owing to the combustion of mill waste was higher for the rubberwood, bamboo, and rattan furniture manufacturing mills. A comparison between the three mills, however, indicated that the rubberwood furniture manufacturing mills released the most amounts of greenhouse gases. This difference is most likely due to the larger amount of mill waste produced by the rubberwood furniture manufacturing industry compared to the bamboo and rattan furniture manufacturing industries.

Table 7. CO_2-eq Emission from Fossil Fuels and Mill Waste

Waste Material	CO_2-eq Emission (kg)	
	Fossil Fuels	Mill Waste
Rubberwood	15.02	70.09
Bamboo	0.20	1.17
Rattan	0.30	1.71

In sum, mill waste has a high potential for electrical energy generation despite its supposedly higher greenhouse gas emission. Because wood is carbon neutral, CO_2 emitted during the direct combustion of the mill waste is considered biogenic carbon. In this context, the utilization of mill waste for energy generation within the furniture manufacturing industries is highly recommended, not only for its potential income but also for its environmental benefit *via* climate change mitigation.

CONCLUSIONS

1. This study investigated the potential use of mill waste produced from the rubberwood, bamboo, and rattan furniture manufacturing activities for electrical energy generation. The conversion of mill waste into potential electrical energy generation was compared with the electrical energy that was consumed by rubberwood, bamboo, and rattan furniture mills, respectively. It was found that a substantial savings in energy cost can be realized through the use of this mill waste.
2. A large amount of mill waste was produced by the rubberwood furniture industry compared to the bamboo and rattan furniture industries. This study indicates that mill waste has the potential to be used as bioenergy and completely substitute for fossil fuels for energy generation to cater to the needs of this industry. In fact, the surplus energy generated from the combustion of the wood waste can also become a potential income earner.
3. In this context, the biomass energy policy in the country must be reviewed to ensure the full exploitation of mill waste for energy generation. Consequently, the utilization of biomass as an energy source can create employment opportunities as well as additional income.

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