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Benchmarking Energy Demand in Medium-Scale Palm Oil Mills: A Comparative Analysis of Electrical and Thermal Intensities Toward Renewable Energy Substitution

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Abstract: *Energy use in palm oil mills remains a critical determinant of both production costs and environmental sustainability. This study analyzed the energy consumption patterns and residue utilization potential in an 8 t/h palm oil mill, aiming to achieve energy self-sufficiency through the effective use of mill residues. The total energy demand was 163.8 kWh/h, equivalent to 20.5 kWh/t FFB, which aligns closely with the electrical energy benchmarks of 18–22 kWh/t FFB reported in recent audits. Kernel cracking, drying, and clarification were the most energy-intensive processes studied. Analysis of solid residues (EFB, mesocarp fibre, and palm kernel shell) revealed sufficient availability to meet the mill's electrical and thermal energy needs when efficiently utilized. However, the recorded mill thermal energy demand (8.9 kWh/t FFB of useful heat) significantly underestimates actual steam requirements, which literature places between 0.14–0.65 t steam/t FFB 600–3000 kWh-th/t. This discrepancy highlights the need to distinguish between useful process heat and gross steam duty when reporting energy balance. The biomass-to-energy balance confirmed the potential for energy self-sufficiency, supporting a transition to renewable energy and circular bioeconomy models. Proper residue management can reduce reliance on fuelwood and fossil fuels, thereby mitigating environmental impacts. This study provides a framework for energy auditing and sustainability assessment in palm oil processing, particularly relevant for sub-Saharan Africa, where energy insecurity and residue accumulation present challenges and opportunities. Future research should focus on optimizing residue conversion technologies and developing integrated energy management systems to enhance the environmental performance of palm oil mills (POMs).*
Keywords*: Energy consumption, Energy substitution, Palm oil mill solid residues, Environmental Sustainability, Renewable energy, Circular bioeconomy*

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I. INTRODUCTION

Palm oil milling is one of the most energy-intensive agro-industrial processes, requiring steady supplies of both electricity and thermal energy for sterilization, clarification, drying, kernel cracking, and auxiliary operations. Benchmark studies indicate that a medium-scale mill typically consumes 20 kWh of electricity per tonne FFB and 0.14 – 0.65 **t** steam per tonne FFB, depending on sterilization cycle and equipment design (Ng et al., 2011; Hasan et al., 2019). In many medium-scale mills, particularly across sub-Saharan Africa and Southeast Asia, energy demand has historically been met through extensive fuelwoodconsumption, which has been associated with significant forest degradation and deforestation (Yusoff, 2006; Mahlia et al., 2019). The continuous harvesting of wood resources diminishes biodiversity, reduces carbon sequestration capacity, and accelerates land-use change, thereby contributing to greenhouse gas (GHG) emissions and climate instability. At the same time, many mills attempt to utilize empty fruit bunches (EFB) directly as boiler fuel due to their abundance; however, EFB has a high moisture content (60–65%), low calorific value, and combustion of this residue generates excessive smoke, particulates, and ash disposal challenges (Ng et al., 2011; Ohimain&Izah, 2013). Such practices create localized air pollution and soil contamination while failing to optimize energy recovery, reinforcing the need for cleaner and more efficient residue management. The dual challenges of forest degradation and unsustainable EFB consumption exemplify the environmental costs of poorly managed palm oil energy systems.

Beyond biomass inefficiencies, palm oil mills are exposed to fossil fuel price volatility and supply risks that disrupt production stability. Diesel, petrol, and grid electricity often used to power auxiliary operations or backup generators are subject to frequent shortages and price fluctuations in Nigeria (Ajayi et al., 2022). The removal of fuel subsidies, foreign exchange constraints and global crude oil market instability have made fossil fuels an unreliable and expensive energy source for mill operators. This economic uncertainty intersects with global climate change imperatives, as the Paris Agreement and Sustainable Development Goals call for rapid substitution of fossil fuels with renewable energy alternatives (IPCC, 2021). In this context, palm oil mills stand at the nexus of climate and energy policy: they face both the burden of rising costs and the obligation to reduce emissions. Importantly, the industry generates a diverse set of residues palm oil mill effluent (POME), empty fruit bunch EFB, mesocarpfibre (MF) and palm kernel shell (PKS) which, if properly utilized, can stabilize energy supply and align with international sustainability commitments. The need to integrate residue-based energy systems is therefore both an economic necessity and a climate-driven obligation.

Consequently, there is a growing recognition that energy cost reduction, environmental sustainability, and energy efficiency must guide the modernization of palm oil mills. Studies have consistently shown that energy recovery from residues not only reduces waste management challenges but also enables energy self-sufficiency, where mills generate sufficient electricity and steam internally to meet operational needs (Abdul-Razak et al., 2017; Hasan et al., 2019; Ng et al., 2011). Mesocarpfibre and PKS, owing to their relatively low moisture content and higher calorific values, have been demonstrated to provide adequate boiler fuel, while surplus EFB can be diverted to composting, pelletization, or biogas production to avoid inefficient direct combustion (Ohimain&Izah, 2013). These transitions embody the principle of energy switching, whereby reliance on traditional fuelwood and fossil fuels is replaced with structured renewable systems. The outcomes include reduced operating costs, enhanced environmental sustainability, and alignment with global climate change mitigation strategies. Furthermore, the shift toward circular bioeconomy models strengthens the role of palm oil mills as not only agricultural processing units but also renewable energy hubs. This integration of energy recovery, cost reduction, and sustainability goals positions the industry as a vital contributor to climate resilience and low-carbon development pathways in the global South.

This study aimed to analyze the energy consumption patterns across various unit processes of an 8 t/h palm oil mill and to compare these patterns with industry benchmarks. Furthermore, it evaluated the environmental impacts of current waste management practices, and the potential for integrating circular bioeconomy renewable energy substitution by utilizing unutilized palm oil mill residues. The ultimate objective was to achieve energy self-sufficiency in medium-scale palm oil mills through the effective utilization of palm oil mill residues.

II. MATERIALS AND METHODS

2.1 Analysis of Palm Mill Plant Energy Demand

The analysis is based on a medium-scale mill processing **8 t** FFB per hour, consistent with benchmarks for Nigerian and Malaysian mills (Ng et al., 2011; Hasan et al., 2019). The operational parameters are 16 h/day for 232 days/year, a typical utilization factor in regional studies (Ajayi et al., 2022). Sufficient and consistent energy application is one of the critical factors for crude oil production in the palm millm hence plant energy demand per ton of FFB processed is taken as the total energy consumption per unit of the total processed FFB along the palm oil extraction value chain (Sommart, 2009: Akolgo*et al*., 2023). The mill utilized a mix of electrical, thermal and manual energies in its production process.

2.2 Process Residues Generation and Waste Management Practices

Assessments of solid residues indicated average values of EFB at 22.3%, MF at 13.8%, and palm kernel shell (PKS) at 5.9% (Figure 3.3). These residues are often left to dry in the fields or used inefficiently as low-grade boiler fuel, contributing to deforestation and greenhouse gas emissions (Abdul-Latif et al., 2021; Hossain et al., 2019). Poorly managed residue piles causes spontaneous fires in MF heaps further resulting in environmental degradation and safety hazards. These challenges necessitate sustainable residue valorization pathways, such as anaerobic co-digestion, which can transform residues into renewable bioenergy while mitigating environmental risks (Hosseini& Wahid, 2014). Also palm oil mill effluent (POME), a thick brownish suspension with a high biochemical and chemical oxygen demand, making it a severe pollutant when untreated (Yahya et al., 2020; Vijayaraghavan et al., 2021). Such discharges cause eutrophication and soil nutrient imbalance (Ngwelem, 2021). Biogas energy recovery systems, offer opportunities to reduce pollution while generating renewable energy (Mokhtar et al., 2022; Yacob et al., 2006) and as such, adopting circular bioeconomy principles can address waste management, energy substitution, and climate change mitigation in the palm-oil industry.

Figure 1: Crude palm oil mill plant with processing stages fruit reception, weighing of fruits, threshing of fruit bunch, furnace, cooking of fruit with wood/EFB, clarifier , dryer and Oil storage

2.3 Estimation of Electrical Energy Demand and Consumption

The electrical energy input method,*Ep*, in kWh, equation 1 by Akolgo et al. (2022) was applied to determine the total energy demand by sub-component of the palm mill by multiplying the electric motor's rated power, efficiency, and time by the hours ofoperation. The motor efficiency was assumed to be 80%

$Ep = \eta;Pt$ (Akolgo et al., 2022). (1)

Where *Ep* is the electrical energy consumed (kWh), P is the rated power of motor (kW), t is the hours of operation (h) and η is the efficiency (assumed to be 80%).

2.4 Estimation of Biomass Wood and Empty Fruit Bunch (EFB) Consumption

The estimation of biomass wood and empty fruit bunch (EFB) consumption in the palm oil mill involves calculating the average weights of three different types of forest fuelwood and EFB used per cooker for fruit processing and multiplied by operational days per year to determine total annual biomass consumption (Akolgo et al., 2022). In medium-scale palm oil mills, fuelwood has a calorific value of approximately 17 MJ kg^{-1}, with efficiencies around 13% due to traditional combustion and sub-optimal furnace designs (Akolgo et al., 2022; Prasertsan&Sajjakulnukit, 2006). EFB's calorific value of 16 MJ kg^{-1}, determined from using a bomb calorimeter is lower at varying with moisture content (Chiew& Shimada, 2013). For estimation, a 30% combustion efficiency was assumed, typical for small and medium-scale biomass boilers in developing countries (Hosseini& Wahid, 2014). The annual biomass fuel mass (W, kg) is converted to energy (MJ) by multiplying with calorific value (CV, J kg^{-1}) and adjusting for combustion efficiency. The energy released is expressed as:

$$Q = W \times CV \times \eta \times CR \quad (2)$$

where Q represents heat released (MJ), W is biomass weight (kg), CV is calorific value (MJ kg^{-1}), η is combustion efficiency, and CR is combustion rate (kg h^{-1}).

2.5 Estimation of Manual Energy

Estimating manual energy demand requires alignment with industrial energy consumption benchmarks. Abdul Razak et al. (2017) reported that manual labour in palm oil mills are converted to energy units to account for human metabolic workload. This accounting reflects the energy substitution potential of the palm mill residues. Manual energy, Me in kW, for FFB loading, furnace heat setting, and residue dumping, was estimated at 0.30 kW with 25% conversion efficiency in tropical climates (Odigboh, cited by Sulaiman et al., 2012 and Akolgo et al., 2022). For an 8-hour workday,

$Me = 0.075Nt$ (kWh) (3.4)

$= 0.075 \times 4 \times 8 = 2.4$ kWh.

where N is persons involved and t is operation time in eight hours.

III. RESULTS AND DISCUSSION

3.1 Palm mill plant energy consumption

Table 1 reveals that the energy demand is distributed among manual, mechanical, heat, and electrical sources, reflecting the diverse energy needs of the palm oil milling process. Based on the mill capacity of 8 t FFB/h the total hourly energy demand of 163.8 kWh/hat 16 h operation for 232 days/yeartranslates to 20.5 kWh/t FFB, in close agreement with the 18–22 kWh/t FFB industry electrical benchmark(Mahlia et al., 2012; Hasanudin et al., 2019). Electrical consumption is dominated by kernel cracking (30 kWh/h), presses, conveyors, and auxiliary drives, yielding a subtotal of approximately 130–135 kWh/h (16–17 kWh/t FFB). This agrees closely with industry norms of 20 kWh/t FFB (Mahlia et al., 2012). Conversely, thermal consumption is represented by sterilization (32.4 kWh/h), drying (25 kWh/h), and clarification (14 kWh/h), yielding a subtotal of 70 kWh/h (9 kWh/t FFB). The values aligns with best practices in industrial energy audits and allows robust comparison with reported benchmarks.

However, the reported sterilization heat of 32.4 kWh/h appears underestimated when benchmarked against the 0.14–0.65 t steam/t FFB requirement documented in Southeast Asian and West African audits (Chavalparit et al., 2006; Vijaya et al., 2008). At 8 t/h throughput, this corresponds to **1.1–5.2 t** steam/h, equivalent to 600–3,000 kWh-th/h, assuming saturated steam at 3–4 bar(g). This suggests that the table reflects useful heat at the process end-use, not the gross boiler duty, underscoring the need to specify steam pressure and enthalpy assumptions. Kernel cracking remains the dominant motor load, as corroborated by Malaysian and Indonesian case studies (Vijaya et al., 2008). Thermal duties in drying (25 kWh/h) and clarification 14 kWh/h fall within reported auxiliary ranges (Mahlia et al., 2012). Minor entries such as lighting **(2.4 kWh/h)** and nut/fibre separation (2 kWh/h) also correspond with “miscellaneous” loads observed in mill audits (Hasanudin et al., 2019).

Significant energy-consuming process-level distribution revealed kernel cracking (30 kWh/h electrical) and drying (25 kWh/h thermal) and clarification (14 kWh)**,**as dominant consumers, consistent with audit reports (Ng et al., 2011) which together account for approximately 52% of the total energy consumed.. However, when benchmarked against steam literature values, the reported thermal load of 8.9 kWh/t FFBorders of magnitude is lower than the expected 600–3000 kWh-th/t. This reveals that the table values accounts only for useful heat delivered to processes, excluding boiler and distribution losses. Without clarification, such under-reporting risks misrepresenting actual biomass fuel requirements.

Manual energy values align with physiological energy conversion and operational realities of medium-scale mills, supporting accurate energy efficiency evaluations. Converting manual work to kWh enables comparison between fossil-fuel, biomass, and renewable bioenergy pathways. Using metabolic equivalents (MET), heavy labour expends 1.5–3.5 MJ per hour or 0.4–1.0 kWh (FAO, 2011). According to Ohimain&Izah (2014), with medium scale employing 60-100 staff, and with 40-50% workforce in energy-intensive tasks, daily metabolic energy reaches 250-400 kWh, aligning with international standards. Including manual energy ensures comprehensive energy flow representation in mills. Singh et al. (2018) emphasized that human energy demand is crucial in small and medium-scale agro-industries with moderate mechanization.

Table 3.5: Palm mill plant energy consumption pattern

S/N	Unit process	Energy type	Energy consumed (kWh)
1	Loading FFB into basket	Manual (4 No)	8.6
2	Lift basket hoist	Mechanical	8
3	Setting furnace heat	Manual (2 No)	2.3
4	Fire blower	Mechanical (8 No)	1.6
5	FFB Sterilization	Steam Heat	32.4
6	Thresher conveyor	Mechanical (2 No)	4
7	Stripper	Mechanical (2 No)	4.2
8.	Digester	Mechanical (2 No)	8
9	Screw press	Mechanical (2 No)	8
10	Crude oil pump	Mechanical (2 No)	3
11	Oil discharge pump	Mechanical (2 No)	8
12	Collection/piling of solid residues	Manual (2 No)	2.3
13	Fibre/Nut separation	Electrical	2
14	Clarification	Heat	14
15	Drying	Heat	25
16	Kernel cracking	Electrical	30
17	Office Lightings etc	Electrical	2.4
		Total	**163.8**

Figure **2** highlights the allocation of energy across sterilization, clarification, drying, and motor-driven processes and the alignment of electrical intensities.

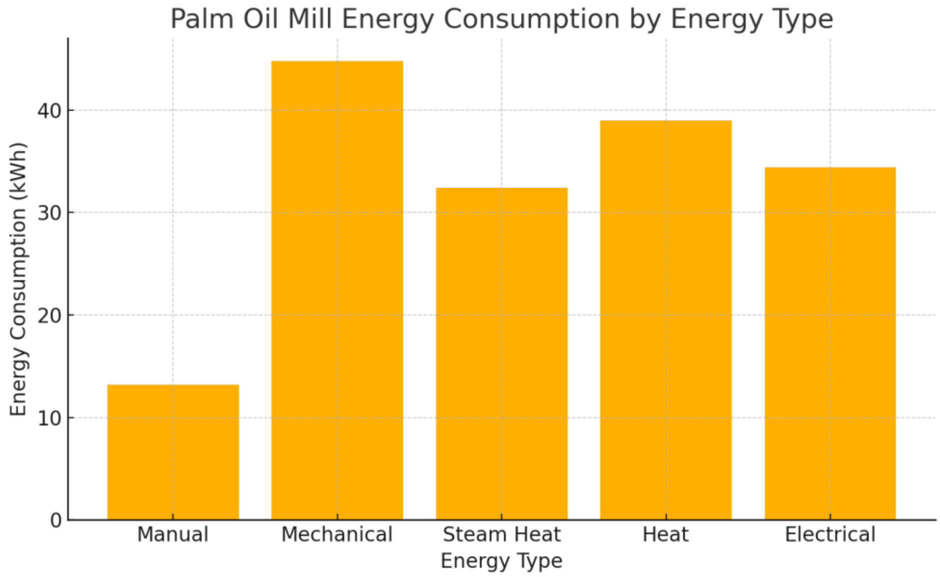


Figure 2: Summarized palm oil mill energy consumption by energy type.

3.2 Analysis of Solid Process Residues Availability as Biogas Feedstock

Theestimated annual production, uses, and sustainable availability of the industry palm solid residues as shown in Tables 4.7 and 4.8. provides insight into the sustainable availability and energy potential of the palm oil mill residues, including empty fruit bunches (EFB), mesocarpfibre (MF), and palm kernel shell (PKS), alongside a composite mix. Table 2 evaluates net residue availability after accounting for competing uses, while Table 3 presents dry matter content, surplus availability factors (SAF), lower heating values (LHV), and conversion efficiencies. These parameters are crucial for estimating the recoverable energy from each residue type (Elbersen, 2013; Abdullah &Sulaiman, 2013). Dry residue fractions highlight moisture-related constraints. EFB, at 0.35, has the highest moisture content, followed by MF (0.60) and PKS (0.85). Despite similar LHVs (16.25–16.62 MJ/kg), the usable energy per kilogram wet feedstock scales with both dryness and conversion efficiency (η = 0.65). Consequently, PKS delivers approximately 9.04 MJ/kg-wet, MF 6.48 MJ/kg-wet, and EFB 3.70 MJ/kg-wet. PKS thus represents the premium solid fuel option on a wet-mass basis, although availability constraints limit its overall contribution. The factor column in Table 4.8 reflects this relationship: EFB (0.0744), MF (0.39), and PKS (0.2763). For the composite, the dry fraction is estimated at 0.624 using SAF-weighted averaging.

The net availability is calculated as the ratio of the balance to the residue product ratio. EFB exhibits 32.7% availability, indicating significant diversion to heat and power (15%). MF demonstrates 100% availability, while PKS is reduced to approximately 58% availability due to partial use as a soil amendment. The final residue availability factor of 0.75 reflects a conservative assumption based on realistic field recovery rates reported by Elbersen (2013). Notably, Table 2 applies a slightly stricter SAF of 0.5 for PKS, which may account for operational uses on-site for road maintenance. Figures 3 and 4 present the graphical comparisons for dry residue fractions, lower heating values, and a combined view (normalized LHV and dry residue fraction) in Figure 5.

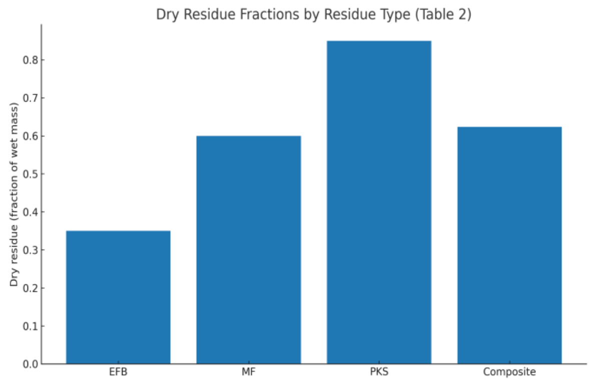
Table 2**:** Estimated annual production, uses, and sustainable availability of oil palm solid residues (dry t ha^{-1} yr^{-1})

S/N	Residue Type	Residue Product Ratio	Other Purpose	Use as soil amendment	Used for heat and Power %	Balance	Net Availability
1	EFB	0.223	0	0	0.15	0.073	32.7
2	MF	0.138	0	0	0	0.138	100
3	PKS	0.059	0	0.025	0	0.034	58
4	POME	0.65	0.15	0	0	0.50	75
				Final residue availability		**0.75**	

Table 3**:** Palm mill solid residues surplus availability and lower heating value (LHV)

S/N	Residue Type	Dry Residues based on wet basis	Surplus availability factor (SAF)	LHV MJ/kg	Conversion efficiency (%)	Factor
1	EFB	0.35	0.327	16.253	0,65	0.0744
2	MF	0.6	1	16.619	0,65	0.39
3	PKS	0.85	0.5	16.359	0,65	0.2763
4	Composite	-	0.60	16.340	0.65	-

ARG is the amount of residue generated annually on a dry basis (tyr-1), PFFB annual palm production (t), $EP_{residues}$ total energy potential per residue (J t-1), SAF surplus availability factor. For the sustainable palm mill residue resource availability, using realistic scenarios reported by Elbersen (2013), an availability factor of 75% in Table 1 was applied.



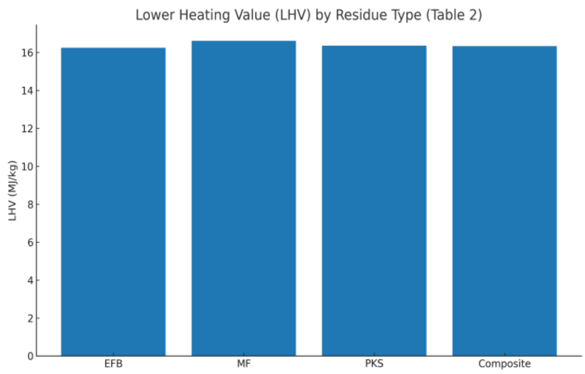


Figure 3: Dry residue fractions by residue type (EFB, MF, PKS, Composite).

Figure 4: Lower heating values (MJ/kg) by residue type

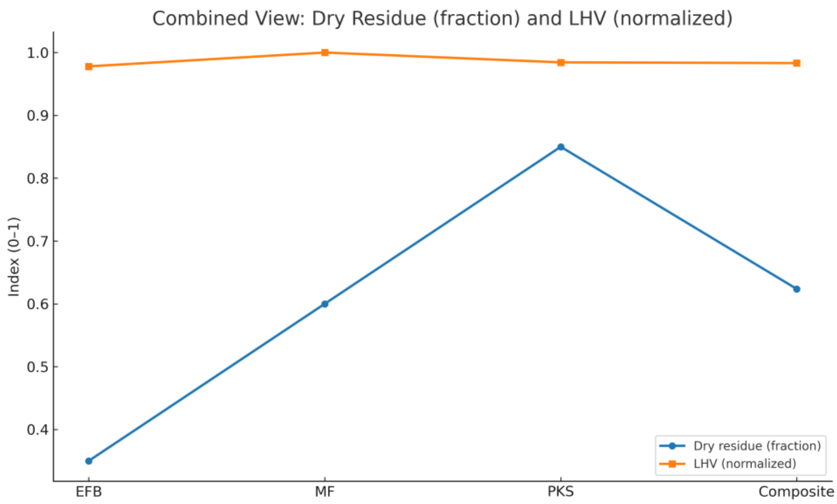


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Figure 5: Combined normalized comparison of dry residue fractions and LHVs

3.3 Biomass-to-Energy Balance Verification

To demonstrate self-sufficiency, the mill's residues mesocarpfibre (13.8% FFB), palm kernel shell (5.9% FFB), and empty fruit bunches (22.3% FFB) can supply the required boiler steam and electricity. With lower heating values of **16–17** MJ/kg forfibre and shell, and 14–16 MJ/kg for EFB (Yusoff, 2006), the annual residue availability is sufficient to meet the combined 20 kWh/t electrical demand and the 0.14–0.65 t/tsteam requirement when corrected for boiler efficiency. This residue-to-energy balance confirms that medium-scale palm oil mills can achieve both electrical and thermal self-sufficiency, supporting the transition toward renewable energy substitution and reinforcing the role of mills in the circular bioeconomy (Hasanudin et al., 2019). By explicitly linking process demand to residue supply, the study provides a robust framework for energy auditing and sustainability assessment in palm oil processing. Residue energy balances suggest that MF and PKS alone, at typical yields of 13.8% and 5.9% of FFB respectively, can supply sufficient boiler fuel to meet both steam and electricity requirements (Ohimain&Izah, 2013). This reinforces the feasibility of energy self-sufficiency, provided reporting practices adequately reflect gross steam demand.

IV. CONCLUSION

The examination of energy consumption patterns in the palm mill revealed a total hourly energy consumption of 163.8 kWh/h (20.5 kWh/t FFB), which aligns with industry benchmarks and provides insights into sustainable energy management. The findings show that the electrical and thermal energy demands meet industry standards, with kernel cracking, drying, and clarification being the most energy-intensive processes. The potential of unutilized solid residues for renewable energy substitution offers alternatives to traditional fuelwood and fossil fuels. The biomass-to-energy balance confirms that the mill can achieve energy self-sufficiency through efficient residue utilization by integrating energy recovery systems, which supports a circular bioeconomy model and the adoption of cleaner production technologies to reduce environmental impacts and costs. By leveraging the energy potential of palm oil mill residues, the industry can contribute to climate change mitigation efforts and enhance economic resilience. Future research should focus on optimizing residue conversion technologies and developing integrated energy management systems to enhance the environmental performance of palm oil mills (POMs). The findings strengthen the case for circular bioenergy substitution pathways in the palm oil industry, particularly in sub-Saharan Africa where fossil fuel costs and energy insecurity remain high.

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