

# Energy Efficiency Improvement in Palm Oil Mills through Waste Heat Recovery and Sustainable Process Integration

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## Abstract

Palm oil mills are energy self-sufficient, and that self-sufficiency has become the principal obstacle to their energy efficiency. Because fibre and shell are burned on site at no accounted cost, thermal losses that would be intolerable in a fuel-purchasing plant persist without scrutiny. This paper reviews the technical basis for energy efficiency improvement in palm oil mills through waste heat recovery and process integration, and establishes where the recoverable losses lie and what determines whether recovery is worth undertaking. A structured review was conducted on peer-reviewed studies indexed in Scopus and SINTA published between 2010 and 2025, covering mill energy and exergy analysis, cogeneration enhancement, waste heat recovery, biogas utilisation, and process integration in agro-industrial plants. Studies were coded for the loss stream addressed, the recovery mechanism proposed, the reported performance, and the analytical method employed. The synthesis identifies four principal loss streams: vented sterilizer exhaust steam, boiler flue gas, engine jacket and exhaust heat from biogas generators, and sterilizer condensate. Mill-scale evidence indicates that recovering these streams within an enhanced cogeneration configuration substantially increases surplus power and, more importantly, extends continuous plant operation. The paper argues that the decisive variable is not thermodynamic recoverability but whether the mill has an accounting framework that assigns a value to internally consumed biomass, and proposes that opportunity-cost pricing of fibre and shell precede technical assessment.

**Keywords:** cogeneration; process integration; waste heat recovery

## Introduction

The palm oil mill is unusual among process plants in that it produces its own fuel as an unavoidable by-product of its primary operation. Mesocarp fibre and palm kernel shell arrive at the boiler continuously and in quantities that, in most configurations, exceed the mill's own steam and power requirement. The mill is therefore energy self-sufficient without deliberate design, and this condition shapes its engineering culture profoundly.

The consequence is that thermal efficiency has weak economic salience. In a plant purchasing natural gas or coal, every avoidable loss is a visible cost, and boiler tuning, insulation, condensate return, and heat recovery are routine capital projects with calculable payback. In a palm oil mill the same losses consume a fuel that appears free, so the payback calculation returns a value close to zero and the project is not undertaken. Umar et al. (2018) identified the wider version of this failure, arguing that treating mill residues as costless fuel has systematically suppressed the development of biomass pathways with higher value.

That framing has weakened as alternative uses have matured. Fibre and shell command prices in export markets; empty fruit bunches have agronomic and materials value that Anyaoha

et al. (2018) and Cheah et al. (2023) document; and surplus electricity can in principle be exported where grid arrangements permit. Once the internally consumed biomass carries an opportunity cost, the entire efficiency calculus changes, and losses that were previously immaterial become recoverable revenue.

The technical literature has established what is recoverable. Booneimsri et al. (2018) analysed an enhanced cogeneration configuration for a forty-five tonne per hour mill, recovering vented sterilization steam, biogas engine waste heat, and empty fruit bunch fuel, and reported surplus power of 2.834 megawatts with crude palm oil production and 4.223 megawatts without it, together with an extension of cogeneration operation from an intermittent 4351 hours per year to 7500 hours and a carbon dioxide reduction of 0.66 million tonnes. Saidur et al. (2010) provided the general energy, exergy, and economic framework for industrial boiler assessment on which such analyses depend. Rajakal et al. (2023) demonstrated more broadly that integrating the palm oil sector with adjacent industries yields outcomes unavailable through plant-isolated optimisation.

What remains underdeveloped is the connection between this technical evidence and the decision environment in which mills actually operate. Studies report recoverable megawatts; mills report that the projects do not pass their investment criteria. This paper therefore reviews waste heat recovery and process integration in palm oil mills with the objective of identifying both the technical opportunity and the accounting condition under which it becomes actionable. The contribution is to make explicit the dependence of the technical case on the valuation of internally consumed biomass, which the engineering literature generally leaves implicit.

## Method

A structured review was conducted on published evidence concerning energy efficiency, waste heat recovery, and process integration in palm oil mills and comparable agro-industrial processing plants.

Records were retrieved from Scopus and from SINTA-accredited national journals for the period 2010 to 2025. Search strings combined plant terms (“palm oil mill”, “crude palm oil”, “agro-industrial plant”) with energy terms (“waste heat recovery”, “cogeneration”, “process integration”, “energy efficiency”, “exergy”, “heat exchanger network”) and outcome terms (“surplus power”, “efficiency”, “emission reduction”). Inclusion required a stated analytical method and a reported quantitative outcome, or an explicit methodological contribution applicable to this plant type.

Extraction recorded the loss stream addressed, its approximate temperature grade where reported, the recovery mechanism proposed, the analytical method employed, the reported performance, and the scale of the study. Temperature grade was recorded because it governs which recovery technologies are thermodynamically appropriate and therefore determines the capital intensity of the solution.

Analysis proceeded by classifying loss streams by grade and matching each to the recovery mechanisms reported for it, then by examining the economic assumptions stated or implied in each study. The second step was necessary because studies differ substantially in whether internally consumed biomass is assigned a cost, and this assumption largely determines the reported attractiveness of the intervention. Since this study synthesises published evidence, no plant measurements were taken and all quantitative values are attributed to their original sources.

## Result and Discussion

### The recoverable loss streams

The reviewed evidence identifies four principal streams. Sterilizer exhaust steam is vented at the end of each cycle and represents the largest single discard, since it is released at process pressure and carries both latent and sensible heat. Boiler flue gas leaves at a temperature determined by the economiser and air heater configuration, and in mills without either it leaves at a grade that is straightforwardly recoverable. Biogas engine jacket water and exhaust constitute a substantial stream in mills that have installed methane capture on effluent. Sterilizer condensate carries both heat and entrained oil, so its recovery serves two purposes at once.

**Table 1. Principal loss streams in a palm oil mill and applicable recovery mechanisms**

| No | Loss stream                         | Grade and character                             | Applicable recovery mechanism                         |
|----|-------------------------------------|-------------------------------------------------|-------------------------------------------------------|
| 1. | Sterilizer vent steam               | Saturated steam at cycle pressure; intermittent | Blowdown accumulator, cascade to lower-pressure users |
| 2. | Boiler flue gas                     | Continuous sensible heat                        | Economiser, combustion air preheat                    |
| 3. | Biogas engine jacket and exhaust    | Continuous; two distinct grades                 | Hot water for process, exhaust boiler                 |
| 4. | Sterilizer condensate               | Hot liquid carrying entrained oil               | Heat exchange plus oil recovery                       |
| 5. | Turbine exhaust and process returns | Low grade, large volume                         | Condensate return, deaerator feed                     |

The intermittency of the sterilizer vent stream is the feature that distinguishes this plant from a continuous process, and it drives the engineering solution. A stream released in pulses at the end of each cycle cannot be matched directly to a continuous demand, so recovery requires either accumulation or a demand that can absorb pulses. This is why the sterilizer vent, despite being the largest single loss, is also the least frequently recovered: the thermodynamic case is obvious while the plant configuration required to exploit it is not trivial.

### From component recovery to process integration

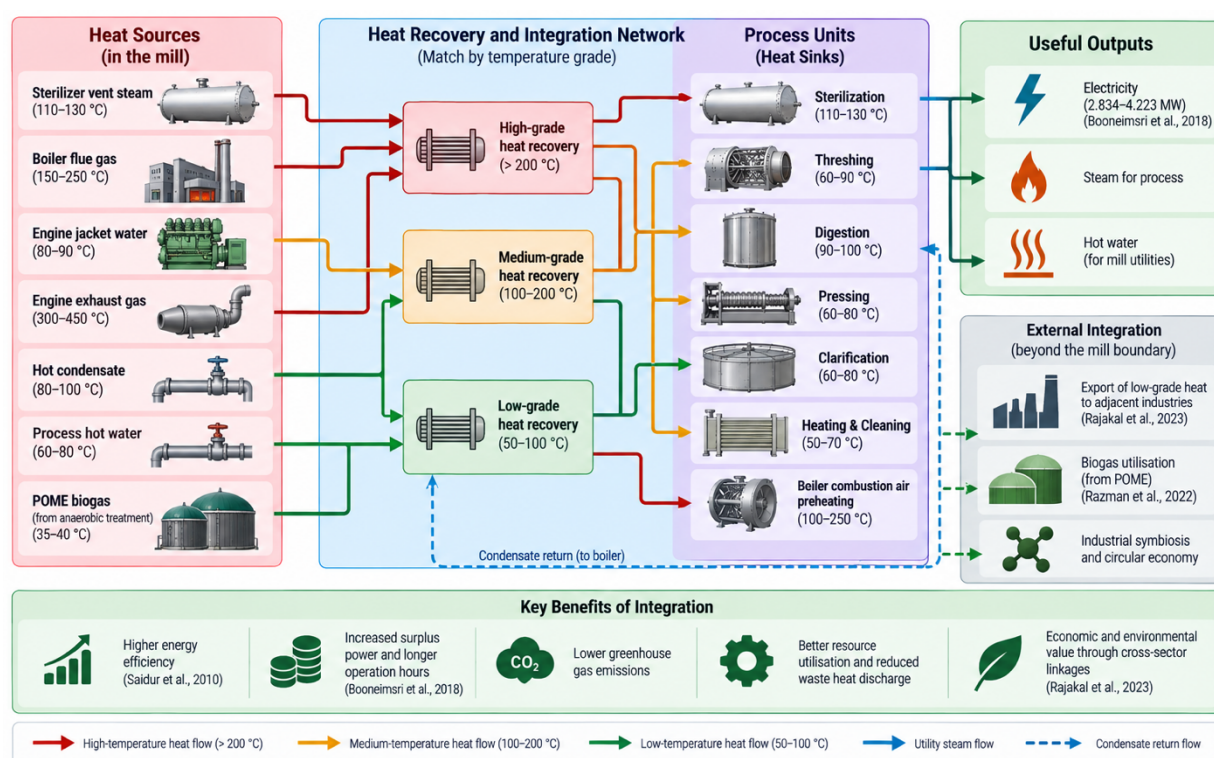
Recovering streams individually yields less than integrating them. Process integration treats the mill as a single network of heat sources and sinks and matches them by temperature grade, so that high-grade heat is reserved for high-grade duties and low-grade heat is cascaded to duties that can accept it. Applied to a palm oil mill, this means that sterilizer vent steam should not be used for a duty that condensate return could serve, and that boiler flue gas should preheat combustion air before it is considered for any process duty.

Booneimsri et al. (2018) demonstrate the aggregate effect of integrated rather than piecemeal recovery. Their configuration combines vented sterilization steam, engine waste heat, and empty fruit bunch fuel, and the resulting surplus of 2.834 and 4.223 megawatts, with and without crude palm oil production respectively, exceeds what any of these measures would deliver alone. The extension of cogeneration operation from 4351 to 7500 hours per year is the operationally more significant outcome, because a plant that runs continuously can support firm supply commitments while one that runs intermittently cannot, regardless of installed capacity.

Saidur et al. (2010) supply the analytical instrument for locating these opportunities. Their treatment of energy, exergy, and economic analysis for industrial boilers establishes that first-law accounting alone understates the opportunity, because it treats a joule of low-grade heat as

equivalent to a joule of high-grade steam. Exergy analysis distinguishes them, and it is precisely this distinction that determines whether a recovered stream can perform useful work or merely displace low-grade heating.

Rajakal et al. (2023) extend integration beyond the plant boundary, showing through optimisation modelling that connecting the palm oil sector to adjacent industries produces circularity outcomes unattainable within a single facility. For energy specifically, this raises the possibility of exporting low-grade heat to a co-located user, which converts a stream that has no internal sink into a saleable product. Razman et al. (2022) address the effluent side of the same integration question through life cycle assessment of integrated membrane treatment of anaerobically treated mill effluent.



**Figure 1. Heat source and sink network in an integrated palm oil mill**

### The accounting condition

The technical evidence establishes that recovery is feasible and that integration outperforms component-level measures. It does not explain why adoption remains limited, and the explanation is not thermodynamic. A mill evaluating an economiser installation calculates the fuel saving, values that fuel at zero because it is fibre it would otherwise have burned, and obtains a payback period that fails its investment threshold. The calculation is arithmetically correct and economically wrong, because the fibre has an alternative use.

Assigning an opportunity cost changes the result. Where fibre and shell can be sold, or where empty fruit bunch fuel displaced by improved efficiency can be sold or diverted to soil amendment with a measurable agronomic return, the saved fuel carries a real price and the same project becomes viable. Hardianto et al. (2023) document the upgrading routes through which mill biomass reaches saleable specification, and Anyaoha et al. (2018) quantify the agronomic

value of the alternative soil pathway. Cheah et al. (2023) and Siagian et al. (2024) establish the wider set of competing uses that give the opportunity cost its magnitude.

Two constraints qualify this argument and should be acknowledged. First, opportunity-cost pricing is only meaningful where a market is actually accessible; a mill remote from a biomass buyer and without grid interconnection faces a genuine zero price regardless of accounting convention, and Umar et al. (2018) note that grid access and tariff arrangements lie outside the mill's control. Second, the reviewed mill-scale analyses are dominated by modelled rather than measured configurations, so the reported surpluses represent thermodynamic potential rather than demonstrated plant performance, and commissioning losses, fouling, and maintenance burden are not fully captured.

## Conclusion

This review examined the technical and economic basis for energy efficiency improvement in palm oil mills through waste heat recovery and process integration. Four recoverable loss streams were identified, of which sterilizer vent steam is the largest and the least frequently recovered, because its intermittent release requires accumulation or a pulse-tolerant sink rather than a simple heat exchanger. Process integration, which matches sources and sinks by temperature grade across the whole plant, delivers more than the sum of component-level measures, and mill-scale analysis indicates that integrated recovery substantially raises surplus power while extending continuous operation from intermittent to near-continuous duty.

The decisive constraint on adoption, however, is an accounting one. Where internally consumed fibre and shell are valued at zero, efficiency projects cannot pass an investment threshold no matter how sound their thermodynamics. Mills should therefore price internally consumed biomass at its accessible market or agronomic opportunity cost before conducting technical assessment, since this single change determines whether the ensuing engineering analysis has any prospect of leading to investment. Further work should report measured performance from mills that have implemented integrated recovery, since the present evidence base is largely modelled and the gap between thermodynamic potential and delivered performance in this plant type remains uncharacterised.

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