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Development of an energy management system for palm oil refinery facilities: implementing a systems approach

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ABSTRACT

This study aims to develop a proactive Energy Management System (EnMS) for a palm oil refinery using a comprehensive systems-based approach implemented carefully during the plant design phase. Unlike conventional methods that rely mainly on historical operational data, this research deliberately utilizes engineering design specifications together with simulation modeling to estimate accurate energy consumption baselines and formulate an ISO 50001-compliant EnMS. A regression-based analysis is systematically applied to define reliable Energy Performance Indicators (EnPIs), using production volume and running hours as key variables influencing overall energy utilization. The resulting analytical model estimates a Specific Energy Consumption (SEC) of 2.168 MWh/MT—significantly higher than the 0.45 MWh/MT BAT benchmark—primarily due to assumptions of full-capacity, simultaneous operation under conservative conditions. To support continuous energy performance improvement, the system incorporates PDCA-based review mechanisms and establishes progressive energy-saving targets: an initial 10% reduction, followed by 1–2% annual incremental improvements. Validation through structured feedback sessions from plant management confirmed the system's strong alignment with operational needs, feasibility within industrial contexts, and readiness for phased implementation. Ultimately, this study contributes a novel, simulation-based framework for integrating EnMS during the design stage, offering a scalable and adaptable model for energy-intensive industries that aim to enhance efficiency and achieve long-term sustainability from the outset.

1. Introduction

The industrial sector constitutes the largest energy-consuming domain globally, accounting for 37% of total final energy consumption, with a substantial portion derived from fossil fuel combustion for heat and electricity generation [1]. Within this context, energy-intensive processing industries, particularly the palm oil refinery sector, face mounting pressure to enhance operational efficiencies and reduce their carbon footprint [2]. Global palm oil production, exceeding 75 million tons annually, is predominantly concentrated in Southeast Asia, with Indonesia and Malaysia as the primary producers [3]. Palm oil refineries are characterized by energy-demanding processes including degumming, neutralization, bleaching, deodorization, fractionation, hydrogenation, and texturization, all requiring substantial thermal and electrical energy inputs [4].

Despite this energy intensity, most refinery facilities in developing regions lack systematic energy management practices, typically relying on reactive measures rather than proactive planning strategies, thereby limiting their energy efficiency potential [5]. Moreover, energy efficiency improvements are commonly introduced only during operational audits, frequently overlooking optimization opportunities available during the design phase [6]. The systems approach to energy management, which emphasizes the integration of organizational structures, processes, and technologies to optimize energy performance across interconnected systems [7], has emerged as a critical framework for achieving sustainable energy efficiency in industrial settings [8]. This holistic approach differs from traditional component-based energy management by analyzing energy flows, process interactions, and operational dependencies across the entire facility as an integrated system [9].

A promising solution lies in implementing structured Energy Management Systems (EnMS) following ISO 50001:2018 recommendations, which promote continuous performance improvement through the Plan-Do-Check-Act (PDCA) cycle [10][11][12]. Multiple studies have demonstrated EnMS effectiveness across various industrial sectors. Apriyanti et al. [13] reported energy savings of 47,700 GJ and CO_2 emission reductions of 11,805.75 tons in the pulp and paper industry. Similarly, Custodio et al. [14] documented an 8% reduction in monthly electricity consumption following ISO 50001 implementation in brick manufacturing, translating to annual savings of 522,048 kWh. However, these studies primarily focused on retrofitting existing facilities with available operational data.

Successful EnMS implementation requires top management commitment, clearly designated energy management roles, and cross-functional collaboration through steering and technical committees [15]. Thollander and Palm [16] identified organizational barriers to energy efficiency, emphasizing that effective implementation demands both technical solutions and systematic organizational change. Karcher [17] further highlighted the importance of integrating energy management into corporate strategy and decision-making processes for sustained performance improvement. Best practices emphasize utilizing Energy Performance Indicators (EnPIs), performance baselines, and normalization techniques to enable accurate energy performance tracking across individual, system, and organizational boundaries [18].

Previous research has demonstrated that integrating energy management into early plant design stages enables more effective equipment selection, layout optimization, and energy performance forecasting [19][20]. Elbeltagi et al. [21] showed that prioritizing energy management from the design outset can achieve up to 25% reduction in building energy consumption. Williams and McKane [22] emphasized that the systems approach to industrial energy efficiency requires considering energy flows and interdependencies from the design phase. However, a critical gap exists: while numerous studies address EnMS implementation in operational facilities, limited research focuses on developing proactive energy management systems using design-phase data and simulation modeling.

The application of Best Available Techniques (BAT) and benchmarking tools such as ISO 50006 strengthens energy-saving opportunity identification in industrial design and operation [23][24][25]. Hehenberger et al. [26] proposed a framework modeling energy-specific properties across various product and process levels, ensuring effective component interaction for energy consumption optimization. Energy Performance Indicators (EnPIs) are crucial for industries to monitor and improve energy efficiency, reduce emissions, and achieve sustainability goals [27][28]. Benchmarking helps identify production process energy inefficiencies, promoting awareness and highlighting potential energy-saving opportunities [29].

In the palm oil industry specifically, existing energy management research reveals significant limitations. Sommart and Pipatmanomai [30] conducted energy audits in operational crude palm oil mills, suggesting boiler retrofitting and heat recovery system enhancement, achieving 7% energy

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savings. Noraini et al. [31] analyzed electrical energy patterns in palm oil mills, identifying efficiency improvement areas with potential savings of 31.49%. However, these studies were limited to existing operational facilities and focused primarily on individual equipment optimization rather than systematic energy management. Lakshmanan et al. [32] discussed sustainable practices in edible oil refining complexes but provided no structured framework for energy management implementation.

Several critical gaps emerge from the literature review. First, existing palm oil refinery energy management studies predominantly focus on operational facilities with available historical data, creating a significant gap in design-phase energy management approaches [30][31][32]. Second, while the systems approach to energy management has been widely advocated in manufacturing industries [7][8][9], its specific application to palm oil refineries using integrated organizational and technical frameworks remains underexplored. Third, the development of EnMS using simulation-based modeling and design data, particularly for ISO 50001 compliance, has not been adequately addressed in palm oil sector literature.

This study aims to develop a proactive Energy Management System (EnMS) for palm oil refineries using a systems approach applied during the plant design phase. The research investigates how engineering design data can estimate energy baselines, structure an ISO 50001-compliant framework, and define Energy Performance Indicators (EnPIs) without relying on historical operational data. By addressing these aspects, this research fills a critical gap in energy management literature—specifically, the absence of system-based methodologies tailored to new industrial facilities before operational commencement.

The study focuses on developing a design-stage energy management system for a large-scale palm and lauric oil refinery in the Sei Mangkei Special Economic Zone (SEZ), North Sumatra, with projected annual capacity exceeding 450,000 metric tons. The facility encompasses multiple processing lines—refining, fractionation, hydrogenation, and texturization—primarily targeting international export markets. In the absence of operational data, the study utilizes engineering design information and simulation-based modeling to estimate energy consumption and structure an ISO 50001-compliant EnMS prior to plant commissioning.

The primary contribution of this research is developing a novel, proactive energy management framework that addresses the critical gap in design-phase energy planning for industrial facilities. Unlike existing approaches relying on post-commissioning operational data, this study presents the first comprehensive methodology for developing an ISO 50001-compliant EnMS using design specifications and simulation modeling specifically for the palm oil refinery sector. The systems approach integrates organizational structures, technical specifications, and performance monitoring systems into a unified framework replicable across energy-intensive manufacturing domains. Furthermore, this research demonstrates the feasibility of using simulation-based EnPI modeling as a performance-planning tool without real-time data, offering a novel and replicable framework for energy-intensive industries pursuing sustainability from inception.

2. Method

The methodology of this study follows a structured approach to develop an Energy Management System (EnMS) for palm oil refineries. It begins with an overview of plant processes to understand energy demands at each production stage, followed by energy parametric design to identify energy sources, estimate process-specific requirements, and create energy flow diagrams. The EnMS design includes formulating an energy policy, establishing an organizational structure, defining management review processes, and setting implementation targets aligned with Best Available Techniques (BAT) standards. Energy Performance Indicators (EnPIs) are measured by determining boundaries, calculating overall energy intensity, and identifying process-specific indicators, supported by illustrative calculations and consumption benchmarking. Finally, the methodology includes an EnMS compliance check through validation by the plant's management team to ensure alignment with operational requirements and readiness for implementation. Fig. 1 exhibits the step-by-step development process of the EnMS in this study.

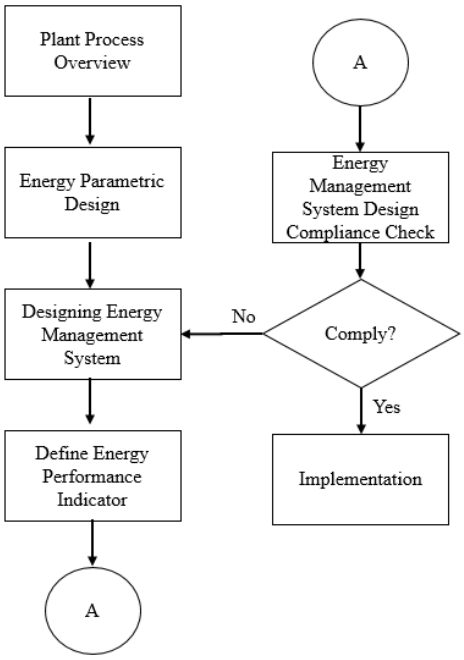

Fig. 1. Steps In The Development Of EnMS

2.1. Plant Process Overview

The palm oil refinery consists of four interconnected main processing plants that transform raw palm oil into specialized products. The Refinery Plants purify raw oils through various processes (CPO washing, semi-continuous palmitic refinery, continuous and semi-continuous lauric refineries) to remove impurities and prepare oils for further processing. The Fractionation Plants then separate refined oils into solid and liquid components based on melting points, including palm oil fractionation, palm stearin fractionation, Crude Palm Kernel Oil (CPKO) fractionation, and enzymatic inter-esterification to rearrange fatty acids for specific applications. The Hydrogenation Plants alter oil saturation levels through controlled chemical processes for both palmitic and lauric oils to increase stability and create solid fats. Finally, the Texturization Plant modifies the consistency of processed fats to meet specific requirements for bakery, frying, and confectionery applications, with the finished products transferred to the Loading Station for packaging and transportation.

2.2. Energy Parametric Design

A theoretical model of the refinery's energy consumption is developed to optimize energy use across the plant. The model identifies key energy parameters that drive consumption and influence efficiency, including a breakdown of energy sources, estimation of energy requirements for each major process, and the creation of energy flow diagrams.

In this study, the energy consumption model focuses on two primary energy types: electricity and thermal energy. These two energy sources are critical because they account for the majority of energy use in the refinery's major processes. The rationale for focusing on electricity and thermal energy is based on their direct impact on operational efficiency and production costs.

The energy consumption estimates for both electricity and thermal energy are based on data generated during the plant design phase, as presented in Table 1. This pre-existing data provides a reliable foundation for modeling energy consumption without the need for additional measurement

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or simulation. It also reflects the energy needs under optimal design conditions, serving as a baseline for the analysis.

Table 1. Energy Consumption of Different Plants in Palm Oil Refinery Facilitiy

No	Plant	Capacity (MTD)	Electricity (MWh)	NG (MWh)	Steam (MWh)
1	**Refinery**				
a	CPO Washing Plant	1000	3.2	-	44
b	CPO Continuous Refinery Plant	1000	15.1	42.28	76
c	CPO Semi Continuous Refinery	300	2.349	41.07	45
d	CPKO Continuous Refinery Plant	200	3.864	10.16	30
e	CPKO Semi Continuous Refinery Plant	200	3.75	27.38	37
2	**Fractionation**				
a	RBDPO Dry Fractination Plant	300	6.15	-	42
b	Hard Stearin Fractination Plant	700	5.95	-	53
c	Enzymatic Inter-Esterification (EIE)	80	1.92	-	5
d	CPKO Fractination	200	1.3	-	39
3	**Hydrogenation**				
a	Hydrogenated Palmitic Plant	250	3.125	-	62
b	CPKO Hydrogenation Plant	200	2.6	-	54
4	**Texturization Plant**	720	45.728	-	122
5	**Package Boiler (2x16 TPH)**			660.60	

The energy flow is visualized in a Sankey diagram, as shown in Fig. 2. This diagram illustrates the amounts of electricity, natural gas, and steam consumed by each plant.

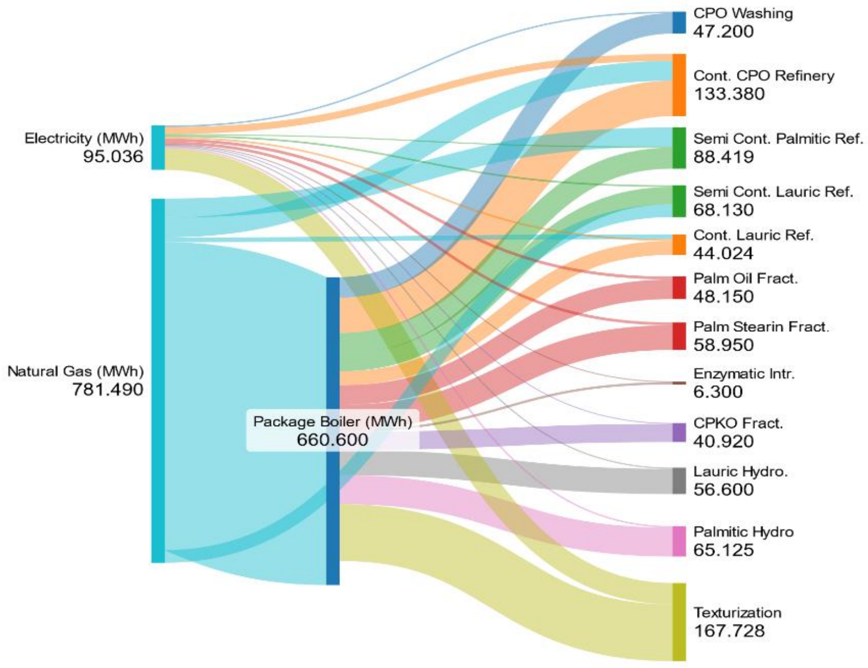

Fig. 2. Energy Flow Diagram

2.3. Designing Energy Management System

The design of an Energy Management System (EnMS) for the palm oil refinery follows a systematic approach to ensure energy efficiency, compliance, and continuous improvement. The development process consists of several key steps as show in the Fig. 3.

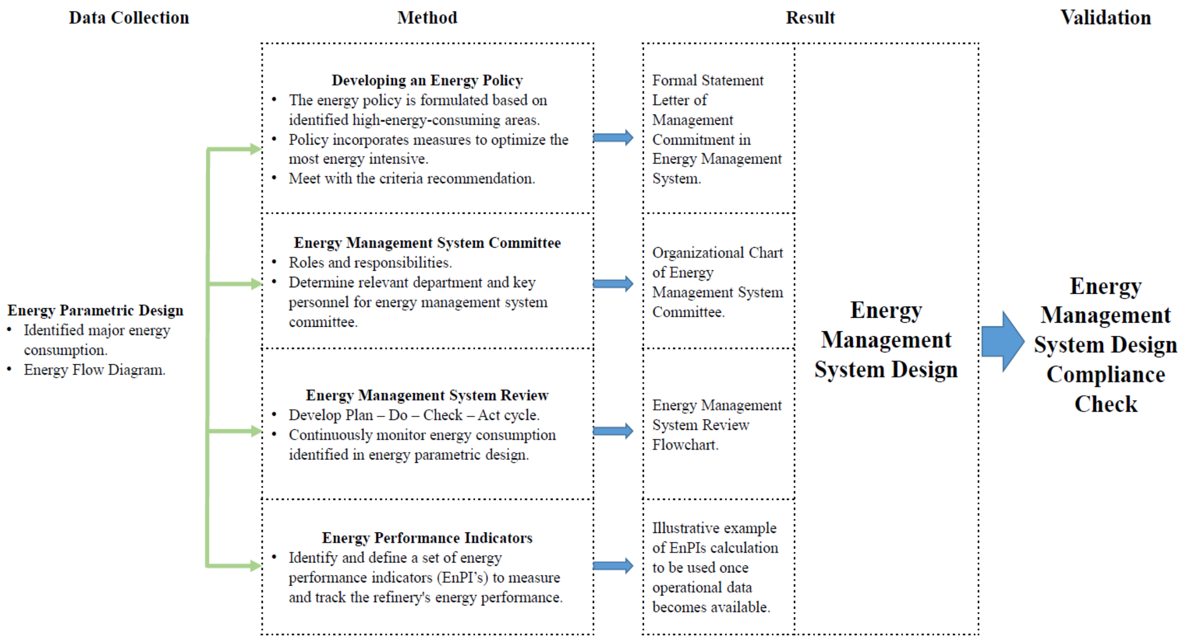

Fig. 3. Designing Energy Management System Flowchart

a. Developing an energy policy

The energy policy serves as the foundation of the EnMS, demonstrating top management's commitment to energy management. Top management shall ensure that the energy policy meets the eight criteria as shown in the Table 2.

Table 2. Developing Energy Policy [33]

No	Criteria	Definition
1	Policy appropriate to energy use	Policy should be appropriate to the nature of, scale of, and impact on the organization's energy use.
2	Commitment to improvement	The energy policy includes a commitment to continual improvement in energy performance.
3	Availability of information and resources	The energy policy includes a commitment to ensuring the availability of information and resources necessary to achieve the stated objectives and targets.
4	Complying with requirements	The energy policy includes a commitment to comply with applicable legal and other requirements to which the organization subscribes and which relate to its energy use.
5	Framework	The energy policy provides the framework for setting and reviewing energy objectives and targets.
6	Program supports energy efficiency	The energy policy supports the purchase of energy efficient products and services.
7	Communication of policy	The energy policy is documented, communicated, and understood within the organization.
8	Policy updating	The energy policy is regularly reviewed and updated as necessary.

b. Energy Management System Committee

The EnMS Committee will be consisted of three departments because of the following considerations:

- Engineering Department has the necessary technical knowledge and understanding of the plant's systems and equipment, which is crucial for identifying energy-saving opportunities and implementing energy-efficient technologies.
- Production Department is responsible for overseeing the day-to-day operations of the plant. Their involvement ensures that energy management practices are integrated into production processes.

- Finance is responsible for tracking the costs associated with energy consumption. Their involvement allows for better analysis of cost savings resulting from energy management initiatives.

Capehart et al. [15] provide a structured framework for developing an organizational chart to support the implementation of an Energy Management System (EnMS). Following this guidance, the company is required to establish a dedicated EnMS Committee responsible for managing and overseeing energy-related initiatives. The committee is structured into five hierarchical levels to ensure clear roles, responsibilities, and communication flow:

a. Top Management
b. Energy Management Coordinator
c. Energy Management Technical Staff
d. Steering Committee
e. Plant Energy Management Coordinator

This study adopts and adapts that framework to suit the organizational context of the case study. The resulting EnMS organizational structure is illustrated in the Fig. 4.

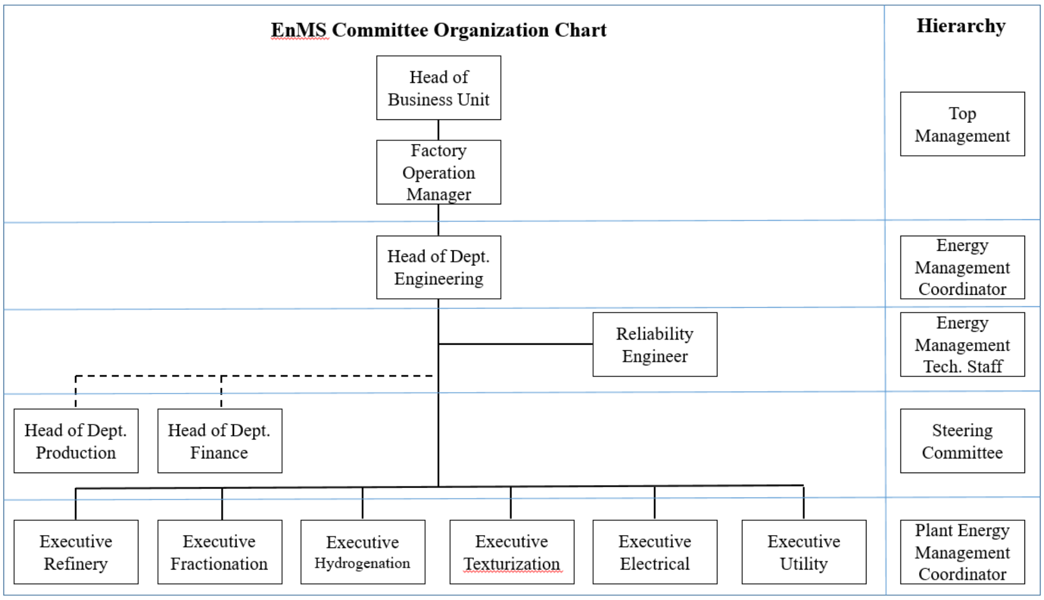

Fig. 4. EnMS Committee Organizational Chart

c. Energy Management System Review

The EnMS review process will be performed using the PDCA (Plan-Do-Check-Act) cycle. The PDCA cycle provides a systematic and iterative approach to managing energy use. By dividing the energy management process into four distinct phases, the organization can continuously refine and improve its energy performance.

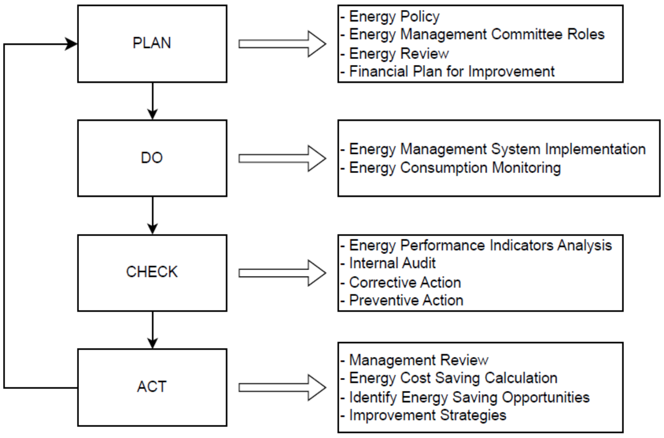

Figure 5. PDCA Cycle for EnMS Review

2.4. Energy Performance Indicators (EnPI) Measurement Simulation

This study will simulate the EnPI calculation for the RBDPO Dry Fractionation Plant with a capacity of 300 TPD. According to common operational practices, this plant is fed with RBDPO and produces 80% RBDOL and 20% RBDST, operating 24 hours a day. Therefore, the baseline data used for the EnPI calculation simulation are given in Table 3.

Table 3. Basis Data Dry Fractionation Plant 300 TPD

Feed	Product 1	Product 2	Energy Consumption
300 TPD RBDPO	80% RBDOL	20% RBDST	48 MWh/day

Based on the data presented in Table 3, the next step is to provide an example dataset that tracks the monthly energy consumption, as shown in Table 4. The following assumptions are applied to the example dataset:

1) The plant operates at full capacity daily.
2) Production rates and energy consumption are assumed to be steady with slight variations in feedstock input month to month.
3) The energy consumption remains consistent at 48 MWh/day.

The assumptions of stable production rates and continuous plant operation, based on design-phase engineering data, are common in early-phase industrial energy modeling to establish a baseline framework [34]. This approach simplifies the initial simulation, allowing for a clearer understanding of the system's potential performance under ideal conditions [35]. Once operational data becomes available, the EnMS can be refined using statistical control methods or time-series forecasting to incorporate variability and uncertainty.

Table 4. Illustrative Example Dataset

Month	Production (MT)	RBDOL (MT)	RBDST (MT)	Running Hours	Measured Energy Cons. (MWh)
Jan	8700	6960	1740	722	1490
Feb	7900	6320	1580	626	1360
Mar	9300	7440	1860	729	1580
Apr	8800	7040	1760	706	1510
May	9100	7280	1820	752	1600
Jun	8600	6880	1720	691	1470
Jul	9300	7440	1860	737	1550
Aug	9400	7520	1880	781	1620
Sep	9000	7200	1800	706	1530

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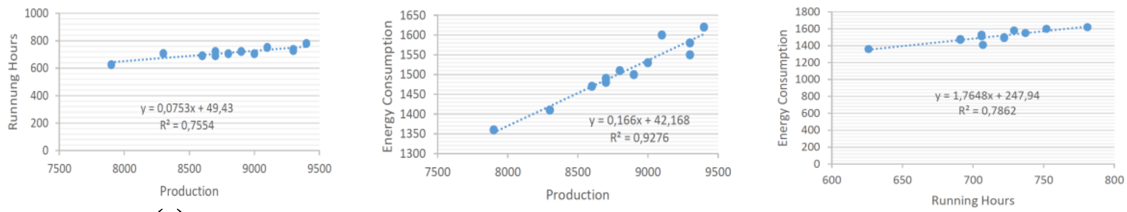
Month	Production (MT)	RBDOL (MT)	RBDST (MT)	Running Hours	Measured Energy Cons. (MWh)
Oct	8900	7120	1780	722	1500
Nov	8700	6960	1740	691	1480
Dec	8300	6640	1660	707	1410

The selection of regression analysis for EnPI modeling is grounded in ISO 50006:2014 guidelines, which recommend statistical methods for establishing energy baselines and performance indicators. Specifically, the standard states that in cases where there is more than one relevant variable, a multiple linear regression or a multivariable regression energy model can be used [18].

The first step in performing the EnPI calculation is to identify the coefficient of determination (R^2) between energy consumption and potentially relevant variables through regression analysis. The Table 5. shows the correlation between all relevant variables and energy consumption, based on the provided scatter diagram which performed by Microsoft Excel as shown in the Fig. 6.

Table 5. Coefficient of determination (R^2)

R^2	Prod	Hours	Energy
Prod	1	-	-
Hours	0.75	1	-
Energy	0.93	0.78	1



(a) (b) (c)

Fig. 6. (a) Production vs Running Hours, (b) Production vs Energy Consumption, (c) Running Hours vs Energy Consumption

The selection of production and running hours as independent variables in the regression-based EnPI model is guided by their direct and measurable influence on energy consumption in process industries. Production reflects the plant's output level, which is a primary driver of energy use in continuous operations. Running hours captures operational time, accounting for fixed energy loads such as thermal and electricity energy. Together, these variables provide a practical and reliable basis for estimating baseline energy performance using design-phase data. This approach aligns with ISO 50006:2023 guidance, which recommends selecting relevant variables that significantly affect energy consumption when establishing performance models [18].

2.5. Energy Management System Design Compliance Check

To ensure the practical relevance of the proposed Energy Management System (EnMS), a structured validation process was conducted involving senior stakeholders from the case study organization. Feedback was obtained through an assessment by the feedback from management based on the results of this study. The form assessed the EnMS design in terms of alignment with organizational goals, clarity of roles and responsibilities, resource adequacy, and feasibility of energy performance monitoring.

3. Results and Discussion

3.1. Energy Policy

The energy policy developed for this refinery reflects the eight key criteria defined in the Method section, including commitments to continuous energy performance improvement, compliance with legal and other applicable requirements, provision of necessary resources, and promotion of energy-efficient procurement. The policy also establishes a framework for setting and reviewing objectives, emphasizes organizational awareness, and ensures regular review and updates by top management. This policy serves as the foundation for the refinery's EnMS and aligns with ISO 50001 standards.

3.2. Modelling Energy Management System Review

The Energy Management System (EnMS) Committee, established in the previous section, will oversee the implementation of the Energy Management System by following the PDCA (Plan-Do-Check-Act) cycle, as illustrated earlier.

The main roles of EnMS Committee will be elaborated into a specific responsibilities and combined with the PDCA cycle. For a better understanding of EnMS Committee in PDCA cycle, it has been provided a flowchart process of Energy Management System Review in the Fig. 7.

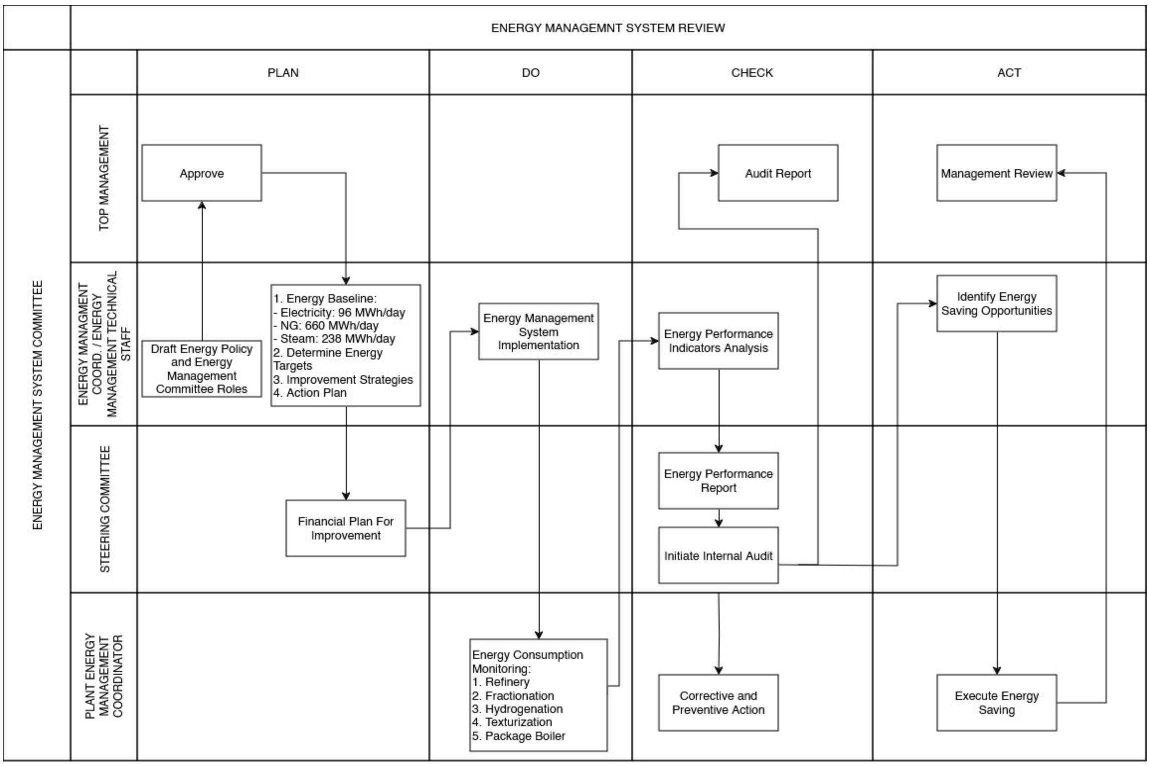


Fig. 7**.** Energy Management System Review

According to the above flowchart, we can specify the responsibilities of each EnMS Committee which is as follows:

1) Top Management
   - Approve the drafted Energy Policy and committee roles.
   - Allocate resources, including funding and personnel, to support energy management initiatives.
   - Review energy performance periodically to ensure alignment with organizational objectives.
   - Identify energy-saving opportunities based on reports and approve corrective actions.

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- Ensure compliance with legal and regulatory requirements related to energy management.

2) Energy Management Coordinator/Technical Staff
    - Draft the Energy Policy and define the roles of the Energy Management System Committee.
    - Develop energy baselines (e.g., electricity, natural gas, and steam consumption).
    - Determine energy targets, improvement strategies, and action plans.
    - Provide technical expertise for implementing the Energy Management System.
    - Perform energy performance analyses and monitor energy performance indicators (EnPI's).
    - Prepare energy performance reports and recommend improvement actions.
    - Facilitate internal audits and support compliance initiatives.
3) Steering Committee
    - Provide guidance on policy development and strategic objectives.
    - Review and endorse financial plans for energy improvement.
    - Monitor the overall progress of the Energy Management System implementation.
    - Assess energy performance reports and audit findings to ensure accountability.
    - Advocate for energy-saving measures and support the identification of opportunities.
    - Participate in management reviews to ensure alignment with organizational goals.
4) Plant Energy Management Coordinator
    - Monitor energy consumption across specific areas of the plant (e.g., refinery, fractionation, hydrogenation, texturization, package boiler).
    - Ensure operational compliance with energy management practices in daily activities.
    - Coordinate with technical staff to implement energy-saving initiatives.
    - Identify and report operational inefficiencies that impact energy performance.
    - Collaborate with internal auditors and provide data for energy performance reviews.
    - Execute corrective and preventive actions in response to audit findings.

3.3. Illustrative Energy Consumption Mapping

The purpose of the energy estimates that were obtained in the Energy Parametric Design is to identify the most energy consumer from all plants. As informed in the previous section, these data were obtained through detailed engineering calculations without historical operational data. This data serves as a reliable baseline for understanding the facility's energy requirements under optimal operating conditions.

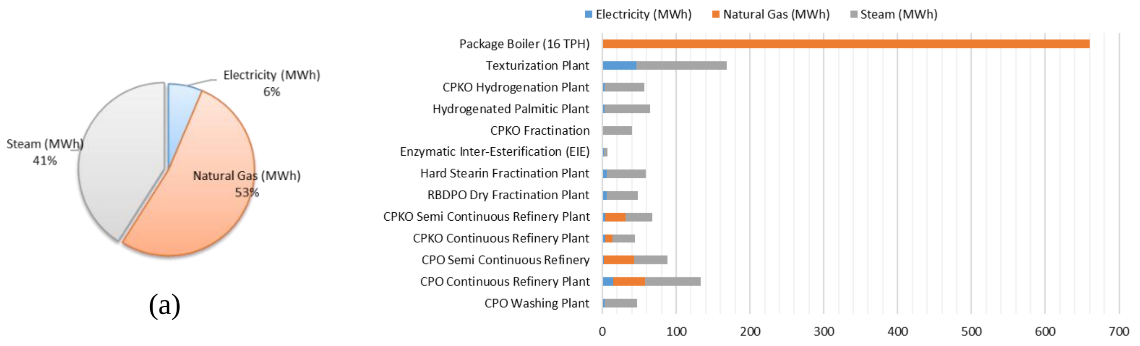
Fig. 8 shows the highest energy required to operate the plant, which is Natural Gas with 53% of total energy. By using this illustration, the energy management committee must have a concern to develop a program on how to optimize the efficiency of natural gas consumption.

Natural gas is the primary energy source in the facility, used exclusively to generate steam from package boiler. As such, optimizing natural gas consumption requires a dual focus: improving boiler efficiency and ensuring efficient use of steam across process units. Capehart et al. [15] identify three key strategies for improving boiler performance:

1. Oxygen/air ratio optimization to maintain proper combustion efficiency,
2. Load management, i.e., matching boiler output to actual steam demand, and
3. Routine maintenance of the boiler and its support systems.

Rossiter and Jones [36] further emphasize the importance of calibrating the natural gas train assembly, including regulators, shutoff valves, and flame supervision controls. Air velocity must be maintained within a proper range to avoid incomplete combustion and wasted energy. According to their findings, a structured maintenance plan for burner systems can achieve annual energy savings of 5–8% in typical process industries.

In addition to combustion-side optimization, improving steam system efficiency—through insulation, steam trap maintenance, and condensate recovery—can reduce unnecessary steam losses and extend the benefit of every unit of natural gas consumed. Together, these measures offer a practical and cost-effective pathway to reduce natural gas demand without major capital investment, especially when implemented as part of a continuous improvement cycle under the EnMS framework.



(a) (b)

Fig. 8. (a) Energy Illustration Distribution, (b) Energy Use of Plant Process

3.4. Energy Management System Implementation Target

In this study, the optimization of the energy system is approached by comparing the preliminary energy data obtained during the plant design phase with the BAT-FDM *(*Best Available Techniques Reference Document for the Food, Drink, and Milk Industries) benchmarks, specifically for stand-alone refining as shown in Table 6.

Table 6. BAT-FDM Reference [37]

Specific process	Unit	Specific energy consumption (yearly average)
Integrated crushing and refining of rapeseeds and/or sunflower seeds	MWh/ton of oil produced	0.45-1.05
Integrated crushing and refining of soybeans		0.65-1.65
Stand-alone refining		0.1-0.45

To facilitate this comparison, the Specific Energy Consumption (SEC) is calculated using the Equation (1):

$$\textit{specific energy consumption} = \frac{\textit{final energy consumption}}{\textit{activity rate}} \tag{1}$$

where:

- Final energy consumption: Total amount of energy consumed by the specific processes concerned during the production period (in the form of heat and electricity).
- Activity rate: Total amount of products or raw materials processed, depending on the specific sector.

Based on the BAT-FDM reference, the specific energy consumption used for comparison includes both electricity and thermal energy. To ensure the relevance of the comparison, only the thermal energy from steam usage is considered, as steam is the primary form of thermal energy that directly impacts the production process. Table 7 presents the plant's designed energy consumption data for electricity and steam.

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Table 7. Specific Energy Consumption

No	Plant	Capacity (TPD)	Electricity (MWh/MT product)	Steam (MWh/MT product)	Total (MWh/MT product)
1	**Refinery**				
a	CPO Washing Plant	1000	0.0032	0.044	0.047
b	CPO Continuous Refinery Plant	1000	0.0151	0.076	0.091
c	CPO Semi Continuous Refinery	300	0.00783	0.151	0.159
d	CPKO Continuous Refinery Plant	200	0.01932	0.150	0.170
e	CPKO Semi Continuous Refinery Plant	200	0.01875	0.184	0.203
2	**Fractionation**				
a	RBDPO Dry Fractionation Plant	300	0.0205	0.139	0.159
b	Hard Stearin Fractionation Plant	700	0.0085	0.076	0.084
c	Enzymatic Inter-Esterification (EIE)	80	0.024	0.063	0.087
d	CPKO Fractionation	200	0.0065	0.195	0.202
3	**Hydrogenation**				
a	Hydrogenated Palmitic Plant	250	0.0125	0.246	0.259
b	CPKO Hydrogenation Plant	200	0.013	0.270	0.283
4	**Texturization Plant**	720	0.255	0.170	0.426
	TOTAL		**0.405**	**1.763**	**2.168**

The simulation results yield a design-phase Specific Energy Consumption (SEC) of 2.168 MWh/MT product, which is significantly higher than the benchmark SEC values reported in literature, such as 0.45 MWh/MT product in operational palm oil refineries. This discrepancy is attributed to fundamental differences in system boundaries and modeling assumptions.

In this study, the simulation assumes that all major processing units—including dry fractionation, hydrogenation, and texturization—operate simultaneously and at full design capacity. In real-world practice, however, these units are typically operated in a demand-driven and sequential manner, not all at once. Operational scheduling often depends on market conditions, product inventory levels, and batch planning, meaning that energy use is distributed more efficiently across time and product types. Consequently, the actual energy consumption per metric ton of refined oil is lower than the design-phase scenario suggests.

This discrepancy also reinforces the relevance of energy efficiency targets. According to Capehart et al. [15], facilities that have not implemented energy management programs in the past 5–10 years can typically achieve up to 10% energy savings through structured improvements. Even in modern and relatively efficient operations, an additional 1–2% efficiency gain is considered achievable with active monitoring and control. Based on this insight, the EnMS in this study adopts these benchmark values as initial energy performance improvement targets, guiding the prioritization of actions during the early operational phase.

To progressively reduce energy consumption and approach the BAT benchmark, the EnMS incorporates concrete actions targeting both quick wins and long-term improvements:

1. Process Integration and Optimization: Detailed analysis of the palm oil refining process can identify energy-saving opportunities [38]. Process integration techniques help in optimizing energy usage across different stages of refining.
2. Heat Recovery: Implementing efficient heat recovery systems can significantly reduce energy consumption. Waste heat recovery, especially from high-temperature processes, can be utilized for preheating or other heating requirements in the refinery [39].
3. Equipment Efficiency: Improving the efficiency of electrical equipment is essential. This includes using high-efficiency motors, optimizing pump operations, and ensuring proper insulation of equipment to minimize heat loss [40][41].

3.5. Illustrative Example Energy Performance Indicators

A regression analysis was performed to establish Energy Performance Indicators (EnPIs) using Microsoft Excel. The analysis examined the correlation between energy consumption and two key variables: total production and running hours. The coefficient of determination (R^2) was used to assess the strength of these relationships, where values closer to 1 indicate stronger correlations. Table 8 presents the results of the regression analysis for the 300 TPD Dry Fractionation Plant.

Table 8. Regression Analysis Result

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	22.21	127.89	0.17	0.87	-267.09	311.52	-267.09	311.52
Production	0.14	0.03	4.68	0.00	0.07	0.20	0.07	0.20
Running Hours	0.40	0.33	1.21	0.26	-0.35	1.16	-0.35	1.16

Based on the results of the regression analysis, the baseline model for expected energy consumption can be expressed using the *Coefficients* provided in the Table 8 as follows:

$$\textit{Expected Energy Consumption}\ \text{(MWh/month)} = 22.21 + 0.41 \times \textit{Total Production}\ \text{(MT)} + 0.40 \times \textit{Running Hours}\ \text{(hours/month)} \quad (2)$$

Equation (2) will be applied during the reporting period to compare expected energy consumption with actual energy consumption, as illustrated in the Fig. 9.

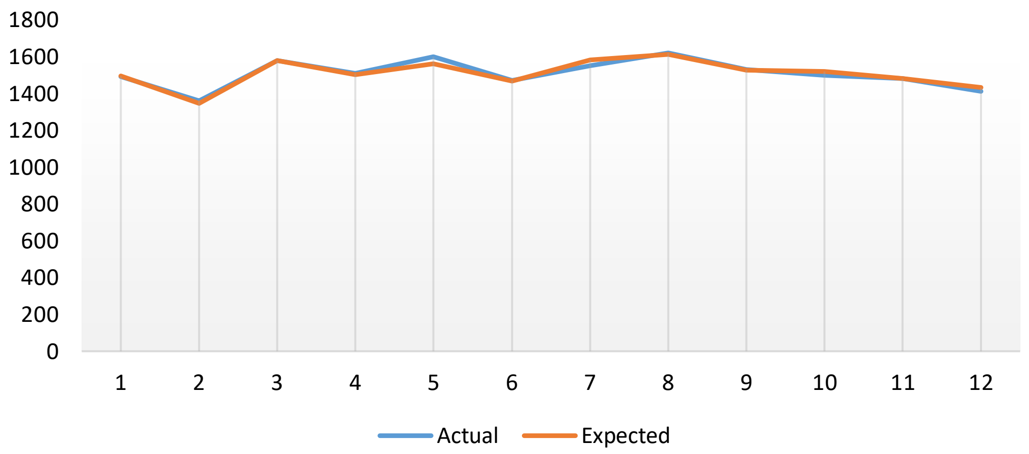

Figure 9. Energy Consumption Actual vs Expected

From the Fig. 8, it is evident that the actual energy consumption closely aligns with the expected energy consumption, indicating good energy performance in this illustrative example.

The Energy Performance Indicators (EnPIs) method outlined above will serve as a key tool for monitoring and evaluating energy performance once the designed EnMS is implemented.

While the illustrative example shows that the actual energy consumption closely aligns with the expected energy consumption based on design assumptions, it is important to note that these assumptions represent idealized operating conditions. In real-world scenarios, several factors could lead to variations in energy performance.

For instance, changes in plant operating schedules—such as partial load operations, intermittent downtime, or batch-based processing—would reduce the total output without proportionally reducing fixed energy loads (e.g., lighting, idle equipment), thereby increasing the specific energy consumption. Similarly, if the product mix shifts (e.g., more hydrogenation or texturization runs, which are energy-intensive), the energy use per ton of finished product would increase. Variations

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in utility system efficiency, ambient temperature, and operator behavior can also influence actual consumption patterns.

These deviations can result in temporary mismatches between actual and expected energy consumption. However, the baseline EnPI established from design data still provides a valid reference point for identifying inefficiencies or changes in performance trends. Once operational data becomes available, the EnPI model can be refined to include real-time variables and seasonal trends, allowing for more accurate tracking and continuous improvement.

3.6. Energy Management System Validation

To assess the feasibility of the proposed EnMS, a structured management validation was conducted using a formal review form. The evaluation addressed key areas relevant to implementation readiness and operational alignment. A summary of the validation outcossmes is provided in the Table 9.

Table 9. Summary of EnMS validation

Validation Area	Key Feedback from Management Review
Alignment with organizational goals	EnMS supports energy efficiency, cost control, and sustainability objectives (e.g., Net Zero initiatives).
Clarity of roles and responsibilities	Roles are clearly defined; ongoing training and cross-functional awareness are recommended.
Resource adequacy	Initial resource planning is sufficient; emphasized maintaining support through the implementation phase.
Energy performance targets	EnPIs and energy goals are considered measurable, realistic, and operationally relevant.
Anticipated challenges	Noted potential impacts from commercial-driven scheduling and operational variability.
Suggestions for improvement	Recommended automation of energy data collection and enhanced monitoring tools.
Priority areas for efficiency	Identified high-load areas such as texturization and fractionation for focused improvement efforts.
Final validation outcome	EnMS design validated for implementation with minor administrative adjustments proposed.

Overall, the EnMS was validated as a practical and comprehensive framework suitable for initial implementation. Management also recommended future refinement of the energy reporting structure and preparation for ISO 50001 certification.

4. Conclusion

This study presents the development of a proactive Energy Management System (EnMS) tailored to a palm oil refinery using a design-phase, system-based approach. Departing from conventional methods that rely on historical energy data, the model utilizes detailed plant specifications to establish performance baselines and identify major energy consumers from the outset. Energy mapping revealed natural gas as the dominant source—constituting 53% of total energy input—and identified the texturization process as the highest electrical load, accounting for 62% of electricity demand.

The EnMS framework integrates structured policies, a defined organizational hierarchy, and role-based responsibilities, supported by performance review cycles using the Plan-Do-Check-Act (PDCA) methodology. The current simulated Specific Energy Consumption (SEC) of 2.168 MWh/MT exceeds the BAT-FDM benchmark of 0.45 MWh/MT due to conservative design-phase assumptions. Nevertheless, the system targets progressive improvements—beginning with a 10%

reduction and annual gains of 1–2% through continuous optimization and energy awareness initiatives.

To support performance monitoring, a set of tailored Energy Performance Indicators (EnPIs) was illustrated using the 300 TPD dry fractionation plant as an example. This example demonstrates how energy baselines and EnPIs can be developed using design-phase data in the absence of operational history. The same approach is planned to be applied across other processing units—including refining, hydrogenation, and texturization—once real-time plant operation begins. These indicators are intended to guide ongoing performance evaluation, benchmarking, and continuous improvement under the EnMS framework.

While the model offers a structured foundation, it assumes steady-state operating conditions and full-load plant operation, which may differ from market-driven, variable production patterns. Implementation challenges may also arise from integration with existing systems and sustaining cross-departmental engagement over time. These risks highlight the need for flexible planning and phased execution supported by management oversight.

The EnMS framework presented here is not limited to palm oil refineries. Its system-based methodology and design-phase modeling approach can be adapted to other energy-intensive sectors, including food processing, chemical manufacturing, and pulp and paper industries.

This research has practical implications for industrial planners seeking to embed energy efficiency into new facility designs, energy consultants developing baseline models for ISO 50001 compliance, and policy-makers advocating early integration of sustainability frameworks. Future work should focus on validating this EnMS through pilot implementation in a post-commissioning environment, incorporating real-time monitoring via IoT sensors, and exploring the use of digital twins for predictive energy modeling and scenario analysis.

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