JOURNAL OF
MECHANICAL ENGINEERING,
SCIENCE, AND INNOVATION
ITATS
Research Article

Analysis of Environmental Indicators Eco-Management and Audit Scheme (EMAS) to Improve Energy Efficiency Using the Sustainable Overall Throughput Effectiveness (SOTE) Indicator in the Production Department (Case Study: XYZ Company, Pasuruan, East Java)

Journal of Mechanical Engineering,
Science, and Innovation
e-ISSN: 2776-3536
2026, Vol. 6, No. 1
DOI: 10.31284/j.jmesi.2026.v6i1.8656
ejurnal.itats.ac.id/jmesi

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Abstract

The rapid increase in global energy demand, driven by industrial growth and the challenges of climate change makes energy efficiency a top priority in the manufacturing sector. Industrial cooling and production processes consume large amounts of electricity and water, contributing to high operational costs and environmental impacts. This research aims to evaluate and improve energy efficiency in a manufacturing production process through the integration of the Sustainable Overall Throughput Effectiveness (SOTE) and Eco Management and Audit Scheme (EMAS) methods. The research was conducted using a case study approach at XYZ Company, a multinational manufacturer of heat exchangers operating in Indonesia. Electricity, washing waste, carbon emission, and water consumption data for 2025 were analyzed, focusing on a selected production process with high energy intensity. The EMAS framework was used to identify sources of energy and water inefficiency through environmental audits, while SOTE was applied to evaluate production performance by considering availability, performance, quality, and sustainability index parameters. The research results indicate that the integration of SOTE and EMAS can provide a comprehensive and structured approach to identifying energy waste without sacrificing the quality of production output. This study proves that improving energy efficiency can be systematically integrated into operational performance management, thereby supporting the achievement of sustainability targets while increasing productivity. This integrated approach provides a practical reference for manufacturing companies in aligning operational excellence with environmental sustainability.

Keywords: *: Energy efficiency, Sustainability, SOTE, EMAS, Manufacturing industry.*

Received: January 26, 2026; Received in revised: March 2, 2026; Accepted: March 5, 2026
Handling Editor: Hasan Maulana

INTRODUCTION

The rapid growth of the global population and urbanization, accompanied by rising environmental temperatures due to climate change has led to a significant increase in the demand for cooling technologies such as air conditioners, refrigeration systems, and industrial cooling equipment. These systems consume large amounts of electrical energy and have become one of the main contributors to energy consumption in the industrial and commercial sectors, [1]. In the manufacturing industry, there are energy intensive processes such as heating, cooling, washing and continuous operation of machines dominate operational activities and directly affect production costs and environmental performance [2].

Globally, the increasing energy demand is still largely met by fossil fuel based energy sources, including coal, petroleum, and natural gas. Nonrenewable energy refers to energy derived from natural resources that are limited and cannot be replenished naturally within a short period. These sources are formed through geological processes over millions of years and include fossil fuels such as coal, petroleum, and natural gas, as well as nuclear fuels like uranium [3]. Globally, the increasing energy demand is still largely met by fossil fuel based sources, and although many countries are beginning to develop renewable energy, they continue to rely on non-renewable energy due to policies, costs, and infrastructure that do not yet support the transition [4]. This dependence raises concerns regarding energy security, resource limitations, and environmental degradation, particularly greenhouse gas emissions that contribute to global warming [1], [5]. International organizations such as the United Nations emphasize the urgency of transitioning to a cleaner and more sustainable energy system as part of the Sustainable Development Goals (SDGs) [6], especially SDG 7 which promotes access to affordable, reliable and sustainable energy. Therefore, increasing energy efficiency has become a strategic priority for the industrial sector as it provides direct benefits in reducing energy consumption, operational costs and environmental impact without requiring large scale infrastructure changes.

The government of Indonesia demonstrates a strong commitment to energy and water conservation through various national policies. Presidential Instruction Number 13 of 2011 explicitly mandates the implementation of energy and water saving initiatives in all government agencies and industrial sectors, and encourages organizations to implement structured and measurable energy efficiency programs [7]. This regulation affirms the importance of systematic energy management to ensure long term resource availability and environmental sustainability.

XYZ Company, as a subsidiary of a global heat exchanger manufacturing company, operates several production facilities in Indonesia and serves domestic and international markets. As part of the company's sustainability strategy, XYZ is committed to reducing electricity and water consumption in its production processes, including a long term target of reducing water usage by 30% by 2030. However, despite this commitment, several production processes still show high energy and water consumption, indicating inefficiencies in operational practices and resource utilization. These inefficiencies not only increase operational costs, but also pose challenges in achieving the company's sustainability targets.

Traditional performance measurement tools in manufacturing, such as Overall Equipment Effectiveness (OEE), generally focus on machine availability, performance, and quality. Although effective in measuring operational efficiency, OEE does not explicitly consider environmental aspects such as energy and water consumption [8]. As a result, energy efficiency initiatives that rely solely on conventional performance indicators may overlook significant opportunities for sustainability improvements. To address these limitations, Sustainable Overall Throughput Effectiveness (SOTE) was introduced as an extension of OEE by integrating sustainability indicators, such as energy use, resource efficiency, resources, and environmental impact, into the production performance evaluation [9]. SOTE expands the scope of conventional OEE giving a new breakthrough by adding environmental impact indicators into machine effectiveness metrics [10].

Previous study have showed that Sustainable Overall Throughput Effectiveness (SOTE) and Eco Management and Audit Scheme (EMAS) provides an internationally recognized managerial framework for evaluating and reporting on a company's environmental performance [11]. Companies are also encouraged to develop realtime energy and water monitoring systems to enable more responsive resource management, which together are expected to significantly reduce water and electricity consumption without compromising product quality [12]. In practice, there is a significant disconnect between the two approaches. The application of SOTE is still often limited to technical optimization on the production floor without synchronization with formal management reporting systems. Conversely, the EMAS framework tends to be administrative in nature and is often not supported by real-time machine performance data. Therefore, this study aims to fill this gap by proposing the integration of SOTE and EMAS as a comprehensive strategic approach.

Combining SOTE's ability to measure operational performance and EMAS's strength in audit management, this research proposes the integration of SOTE and EMAS as a strategic approach to improve energy efficiency in manufacturing operations. It offers a comprehensive framework in managing sustainable manufacturing performance. EMAS serves as an environmental audit and management tool to identify inefficiencies and ensure compliance with regulations, while SOTE quantitatively measures how sustainability factors affect production throughput. This integrated approach enables companies to align environmental goals with operational performance, thereby supporting continuous improvement and strategic decision making. The combination of the two method could give manufacturing companies a chance to systematically reduce energy and water consumption while maintaining production effectiveness and competitiveness. This research focuses on a selected production process at XYZ Company that has high electricity and water consumption, using operational data from 2024. The results of this study are expected to provide practical insights for the manufacturing industry that wants to align productivity improvements with environmental sustainability, especially in the context of developing countries.

RESEARCH METODOLOGY

Research Design

This research uses a quantitative case study approach to evaluate energy efficiency in a manufacturing production process through the integration of the Sustainable Overall Throughput Effectiveness (SOTE) and Eco management and Audit Scheme (EMAS) methods. This integration goes beyond existing frameworks by moving from static reporting to dynamic performance tracking. Unlike traditional OEE, which focuses on productivity alone, the EMAS and SOTE synergy ensures that energy inefficiency is treated as a production loss, thereby making sustainability a core component of operational excellence rather than a separate regulatory burden. The case study method was chosen because it allows for an in depth analysis of energy consumption and operational performance in a real industrial environment. This research focuses on identifying energy inefficiencies and evaluating sustainability oriented performance indicators without changing the existing production system.

The research was carried out in the production department of Company XYZ, a multinational manufacturing company operating in Indonesia. The production process chosen is a process with relatively high electricity and water consumption compared to other processes. The evaluation focused on increasing energy efficiency while maintaining production quality and throughput.

Research Scope and Limitations

The scope of this research is limited to the analysis of electricity and water consumption in a single production process. The operational data used is data from 2024. This research does not include other forms of energy such as compressed air or fuel based energy. In addition, carbon emission calculations were not explicitly analyzed, but rather sustainability performance was evaluated through energy and water efficiency indicators.

Several assumptions were applied in this research. First, all production machines are assumed to be in good operating condition during the observation period. Second, the energy supply is assumed to be stable without significant fluctuations. Third, production demand and product specifications are assumed to be relatively constant during the data collection period.

Data Collection Methods

Data collection was carried out through primary and secondary data sources. Primary data was obtained through direct observation of the production process, on-site monitoring, and interviews with production and maintenance personnel to understand operational conditions. Secondary data was collected from company records, including electricity and water consumption reports, production output data, machine operating hours, and maintenance records.

Energy consumption data was obtained from installed monitoring systems and utility records. Electricity consumption is recorded in kilowatt hours (kWh), while water consumption is measured in cubic meters (m^3). Production data includes total output, defect rates, and operating time. All data was verified to ensure consistency and reliability before analysis.

EMAS Based Environmental Audit

Electricity is widely used across industries, households, and transportation; however, the continuously increasing consumption highlights the need for effective management. [13] stated that optimizing electricity use in construction and industrial sectors can reduce operational costs and positively impact the environment. While organizations certified under ISO 14001 are often found to be less transparent and less committed to environmental performance [14], EMAS is an environmental management system regulated by the European Union that encourages companies to evaluate, report, and improve their environmental performance, including energy efficiency [15]. The adoption of structured environmental management systems such as EMAS is strategically important, as the Dow Jones Sustainability Index (DJSI) identifies companies demonstrating leadership in sustainability through environmentally and socially responsible policies [16]. In addition, Water Source Protection structures are constructed to safeguard springs from contamination and are equipped with collection basins, reflecting regulatory practices in water management [17]. The EMAS framework is applied as an environmental audit tool to identify inefficiencies in energy and water use within selected production processes. The audit follows the Plan-Do-Check-Act (PDCA) cycle, which is the core principle of EMAS: the planning stage identifies significant aspects of energy and water use; the implementation phase monitors resource consumption and operational practices; the inspection stage compares actual consumption with internal benchmarks and sustainability targets to identify inefficiencies; and the action stage formulates recommendations to reduce consumption. Results from the EMAS audit are then used as input in preparing sustainability indicators in the SOTE calculation. Electricity itself is a form of energy generated by the movement of electric charges, either as current or voltage, and can be classified into two main categories in physics and static electricity (stationary charges) [18]. Results from the EMAS audit are then used as input in preparing sustainability indicators in the SOTE calculation. Quality defined as "fitness for use," meaning that a product must function as intended and meet user requirements, highlighting that sustainability initiatives must not compromise product quality [19].

SOTE Performance Measurement

SOTE is used to evaluate production performance by integrating sustainability considerations into the measurement of throughput effectiveness. The SOTE index consists of four main components: Availability (A), Performance (P), Quality (Q), and Sustainability Index (S). Availability represents the proportion of actual operating time to planned production time. Performance reflects the actual production rate compared to the ideal rate, while Quality indicates the ratio of good products to total production output.

The Sustainability Index represents resource efficiency, specifically electricity and water consumption per unit of output. This index is developed based on normalized energy and water usage data obtained from EMAS audits. The SOTE value is calculated using the general equation as follows (Eq.1):

$$\text{SOTE} = A \times P \times Q \times S \qquad (1)$$

This formulation enables sustainability performance to directly influence overall production effectiveness, thereby ensuring that efficiency improvements do not overlook broader environmental or social considerations.

Data Analysis Procedure

Data analysis is carried out through several stages. The first stage is descriptive analysis to evaluate whether the observed data variability was reasonable across the study period using distributional characteristics such as mean, standard deviation, minimum, and maximum values were calculate. In order to know data validity and detect potential abnormal observations, outlier screening was carried out using boxplot visualization and standardized Z-scores. Observations exceeding the acceptable standardized range were considered potential outliers, as extreme values may indicate measurement inconsistencies or non representative operational conditions. Reliability of the dataset was assessed through correlation based consistency checks. Pearson correlation analysis was applied to evaluate the stability of relationships among environmental indicators, while temporal consistency across months was examined using lag based correlation measures.

The second stage is the analysis of EMAS audit results transformed into intensity measures per unit throughput. This approach allows performance evaluation independent of production volume and provides a more equitable comparison across months. The environmental intensity for each indicator was computed as Eq.2. Where I_k represents the intensity per unit output, X_k is the monthly environmental indicator, and T denotes monthly throughput. The third stage is the calculation of the SOTE indicator to evaluate production effectiveness from an operational and sustainability perspective. Sustainability index using Min-Max inversion normalization method that calculated by Eq.3:

$$I_k = \frac{X_k}{T} \qquad (2)$$

$$N_k = \frac{X_{Max} - X}{X_{Max} - X_{Min}} \qquad (3)$$

Where N_k represents normalization score for each indicator, X is each indicator for each month, X_{Min} is minimum score of each indicator, and X_{Max} is maximum score of each indicator. The results of normalization values bounded between 0 and 1, where 1 indicates the most efficient condition and 0 represents the least efficient condition within the observation period. Subsequently, indicator weights were assigned using an equal weighting approach, where each environmental variable contributes proportionally to the composite sustainability measure. The weight for each indicator was defined as Eq.4. Where m is the total number of environmental indicators included in the assessment. The overall Sustainability Index (S) was then computed as a weighted aggregation of the normalized indicators (Eq.5):

$$w_k = \frac{1}{m} \tag{4}$$

$$S = \sum_{k=1}^{m} w_k N_k \tag{5}$$

This index reflects the combined environmental performance of the production system on a monthly basis. Finally, the Sustainable Overall Throughput Effectiveness (SOTE) metric was calculated by integrating operational effectiveness with sustainability performance. SOTE was obtained by multiplying the Sustainability Index with the monthly Overall Equipment Effectiveness (OEE) (Eq.6):

$$SOTE_{anually} = \frac{\sum_{k=1}^{12}(SOTE_k \times Throughput_k)}{\sum_{k=1}^{12} Throughpu\ _k} \tag{6}$$

This integrated indicator enables simultaneous evaluation of production efficiency and environmental sustainability, providing a comprehensive measure of sustainable manufacturing performance over time. Furthermore, a comparative analysis is carried out between the initial conditions and potential improvement scenarios to assess the impact of energy efficiency initiatives. The analysis results are interpreted to determine the influence of energy and water efficiency on production performance and sustainability achievements.

Research Flow

Overall, the research flow includes the identification of processes with high energy intensity, data collection and validation, the implementation of EMAS based environmental audits, the calculation of SOTE performance, and the evaluation of energy efficiency improvement opportunities. This structured approach ensures that sustainability considerations are systematically integrated into the assessment of manufacturing performance.

Case Study

This research aims to evaluate the sustainability performance of the washing process in the heat exchanger production line at PT XYZ through the integration of the Eco Management and Audit Scheme (EMAS) and Sustainable Overall Throughput Effectiveness (SOTE) methods. The evaluation is carried out by combining operational effectiveness indicators and environmental indicators, thereby providing a more comprehensive picture of production performance compared to conventional approaches that only focus on machine productivity.

RESULTS AND DISCUSSIONS

Validity of Research Variables

The initial analysis focuses on verifying the validity and reliability of operational data, including total clean water usage, washing process water consumption, waste generation, electricity consumption, and carbon emissions. These variables were observed over a twelve-month period to ensure a comprehensive representation of annual operational dynamics, as detailed in the descriptive statistics in Table 1.

Table 1. Descriptive statistics of operational variables

Variable	N	Minimum	Maximum	Mean	Standard Deviation
Total Clean Water (m^3)	12	1205.00	1789.00	1534.67	126.25
Washing Clean Water (m^3)	12	348.53	517.44	444.19	36.61
Washing Waste (m^3)	12	296.29	439.88	377.56	31.12
Washing Machine Electricity Consumption (kWh)	12	453.09	672.68	577.36	47.66
Carbon Emissions (TCO2e)	12	385.13	571.78	490.76	40.51

Table 2. Outlier detection results using Z-score

Variable	Z-score Minimum	Z-score Maximum	Decision
Total Clean Water (m^3)	-1.805	1.793	No outlier
Washing Clean Water (m^3)	-1.570	1.702	No outlier
Washing Waste (m^3)	-1.570	1.702	No outlier
Washing Machine Electricity Consumption (kWh)	-1.570	1.702	No outlier
Carbon Emissions (TCO2e)	-1.570	1.702	No outlier

The results of descriptive statistical analysis show that all variables have a range of values, averages, and standard deviations that are within reasonable operational limits. No missing values were found in all variables, hence the data is considered complete and representative. Outlier detection using graphical (boxplot) and numerical (Z-score) approaches shows that all values are within the range of ±3, which indicates the absence of extreme outliers. Thus, the data is declared valid and suitable for use in further analysis.

Outlier detection was performed to ensure that the operational data used in the analysis was not influenced by extreme values that could potentially bias the calculation of Sustainable Overall Throughput Effectiveness (SOTE). Outlier identification was performed using a combination of graphical and numerical approaches, namely boxplot visualization and Z-score calculation as shown in Table 2. The output shown that there is no extreme values. These results were reinforced by the Z-score calculation, which showed that all values were within the range of ±3, therefore it can be concluded that the dataset does not contain outliers and is suitable for further analysis.

Research Variable Reliability

The reliability of research variables aims to ensure that the operational data used is stable and consistent in representing the condition of the production process throughout the observation period. Reliability in this study is not only reviewed from the stability of variable values, but also from the consistency of the relationship between variables and the stability of data change patterns over time. The reliability approach is carried out through correlation analysis between operational variables and temporal correlation (time lag) to ensure that data fluctuations reflect actual operational dynamics, not due to inconsistencies or errors in data recording. The results are presented in Table 3.

Correlation analysis between variables was carried out to assess the consistency of the cause and effect relationship between operational indicators in the context of the production process mechanism. All values are indicates $p - value < \alpha(0.05)$ meaning the relationships among the variables are statistically significant. These results indicate that the operational relationships follow a stable and non random pattern, suggesting

Table 3. Results of significance test of correlation between operational variables

Variabel	Total Clean Water	Washing Clean Water	Washing Waste	Washing Machine Electricity (kWh)	Carbon Emissions
Total Clean Water (m^3)	0.024	0.024	0.024	0.024	0.024
Washing Clean Water (m^3)	0.024	-	0.000	0.000	0.000
Washing Waste (m^3)	0.024	0.000	-	0.000	0.000
Washing Machine Electricity (kWh)	0.024	0.000	0.000	-	0.000
Carbon Emissions (TCO2e)	0.024	0.000	0.000	0.000	-

Table 4. Results of time series correlation

Variable	Correlation Coefficient	P-value	Decision
Total Clean Water (m^3)	0.453	0.162	Not significant
Washing Clean Water (m^3)	0.445	0.170	Not significant
Washing Waste (m^3)	0.445	0.170	Not significant
Washing Machine Electricity Consumption (kWh)	0.445	0.170	Not significant
Carbon Emissions (TCO2e)	0.445	0.170	Not significant

high data reliability, as changes in one variable are consistently accompanied by logical changes in the other variables.The test results show a stable relationship between environmental variables, which indicates that changes in one variable are followed by changes in other variables proportionally according to the characteristics of the washing process. The consistency of this correlation pattern reinforces that the data used has adequate reliability for further SOTE analysis. While time corellation between variables shown on Table 4.

These results show that the operational relationship pattern is declared stable and not random, thus indicating that the data has high reliability because changes in one variable are consistently followed by logical changes in other variables. In addition to the correlation between variables, data reliability was also tested through time series correlation analysis to assess the stability of the pattern of changes in value from one period to the next. The analysis results show that all variables have a lag-1 correlation coefficient in the range of 0.44-0.45, which is included in the medium correlation category. However, the p-value of all variables is above the significance limit (p-value > 0.05), which indicates that changes in value do not follow a certain time trend. This condition indicates that data fluctuations are more influenced by actual operational dynamics than by systematic time patterns. Thus, although the temporal correlation is not significant, the data is still declared reliable because it reflects the real conditions of the production process.

Based on the results of the correlation analysis between variables and time-series correlation, all operational variables are declared to have adequate reliability. The data shows the consistency of the relationship between indicators and fluctuations that are still within the limits of reasonable operational dynamics. Therefore, the research dataset is declared reliable and suitable for use in the Sustainable Overall Throughput Effectiveness (SOTE) analysis stage.

Results of the EMAS Method

The application of the Eco Management and Audit Scheme (EMAS) method in this study aims to quantitatively evaluate the environmental performance of the washing process through key operational indicators, namely total clean water usage, washing clean water usage, washing waste generation, washing machine electricity consumption, and carbon emissions. EMAS analysis was conducted to identify the level of resource utilization efficiency and potential environmental inefficiencies that occurred during the observation period. The analysis stages include calculating environmental intensity per production unit, indicator normalization, indicator weighting, and calculating the Sustainability Index as the basis for integration with the Sustainable Overall Throughput Effectiveness (SOTE) method. To eliminate bias due to throughput variations between periods, all environmental indicators were converted into intensity per production unit. This approach allows for a more objective and proportional comparison of environmental performance. The results of each indicators calculates per unit for each months through 2025 shown in Table 5.

The results of the per unit indicator intensity calculations show fluctuations in resource usage in producing one unit of output each month. The total clean water indicator shows the most significant fluctuations, especially in the period from January to April, which indicates the potential for water wastage compared to other indicators that have relatively small variations. In addition, the comparison between the number of production units and the intensity of resource usage shows an unstable pattern, where increased production in some months is actually followed by a decrease in resource usage efficiency. Furthermore, total clean water consumption per unit becomes the indicator with the largest fluctuations, especially during periods of low throughput. After that, each indicators converted into normalization which range between 0-1 shown on Table 6.

The intensity values of each indicator have different units and ranges, consequently a normalization process is needed to equalize the measurement scale. Normalization is carried out using the Min-Max Inversion method, thereby scaling all indicator values between 0 and 1. Within this framework, values approaching 1 signify more efficient environmental performance, whereas values near 0 reflect higher resource consumption

Table 5. Variable data per unit

Month	Through-put	Total Clean Water (m^3/ Unit)	Washing Clean Water (m^3/ Unit)	Washing Waste (m^3/ Unit)	Washing Machine Electricity (KWh/Unit)	Carbon Emission (TCO2e/ Unit)
January	214	8.360	2.418	2.056	3.143	2.672
February	232	6.487	1.876	1.595	2.439	2.073
March	232	6.302	1.823	1.549	2.369	2.014
April	252	4.782	1.383	1.176	1.798	1.528
May	255	6.137	1.775	1.509	2.308	1.962
June	255	6.125	1.772	1.506	2.303	1.958
July	248	6.161	1.784	1.517	2.315	1.967
August	250	6.168	1.784	1.516	2.318	1.970
September	247	6.065	1.755	1.491	2.280	1.938
October	252	6.230	1.806	1.535	2.345	1.993
November	254	6.252	1.812	1.540	2.357	2.003
December	256	6.258	1.814	1.542	2.363	2.008

Table 6. Variable normalization

Month	Total Clean Water	Washing Clean Water	Washing Waste	Washing Machine Electricity Consumption	Carbon Emissions
January	0.000	0.000	0.000	0.000	0.000
February	0.523	0.523	0.523	0.523	0.523
March	0.575	0.575	0.575	0.575	0.575
April	1.000	1.000	1.000	1.000	1.000
May	0.621	0.621	0.621	0.621	0.621
June	0.624	0.624	0.624	0.624	0.624
July	0.614	0.612	0.612	0.616	0.616
August	0.613	0.613	0.613	0.613	0.613
September	0.641	0.641	0.641	0.642	0.642
October	0.595	0.592	0.592	0.593	0.593
November	0.589	0.586	0.586	0.585	0.585
December	0.587	0.583	0.583	0.580	0.580

Table 7. Variable weighting

Variable	Weight
Total Clean Water (m^3)	0.20
Washing Clean Water (m^3)	0.20
Washing Waste (m^3)	0.20
Washing Machine Electricity Consumption (kWh)	0.20
Carbon Emissions (TCO2e)	0.20

or environmental burden. Notably, January consistently yields a value of 0 across all sustainability indicators. This normalization procedure ensures that each indicator contributes equitably to the formation of the sustainability index.

After the normalization process, indicator weighting was carried out to determine the relative contribution level of each indicator to overall environmental performance. Weighting is carried out with the assumption that all environmental indicators have an equal level of importance in reflecting the sustainability performance of the washing process showed on Table 7.

All indicators are assigned a uniform weight of 0.20 to prevent the dominance of specific variables within the final index. This equal weighting ensures that each indicator contributes proportionally to the environmental performance assessment, thereby facilitating a more objective and consistent interpretation of the results throughout the observation period. The Sustainability Index value is in the range of 0-1, where a value close to 1 indicates increasingly efficient and sustainable environmental performance. The calculation results show variations in index values between periods which reflect the operational dynamics of the production process. Periods with higher index values indicate better resource usage efficiency, while lower values indicate potential inefficiencies that can be used as a basis for continuous improvement. Thus, the Sustainability index calculates for each months to show the movement increase or decrease. The output of sustainability index every month explain on Table 8 below.

In order to visualize movement detail of each months, Figure 1 shown sustainability Index on the graph.

Table 8. Sustainability index every month

Month	Sustainability Index (S)
January	0.000
February	0.523
March	0.575
April	1.000
May	0.621
June	0.624
July	0.614
August	0.613
September	0.641
October	0.593
November	0.586
December	0.583

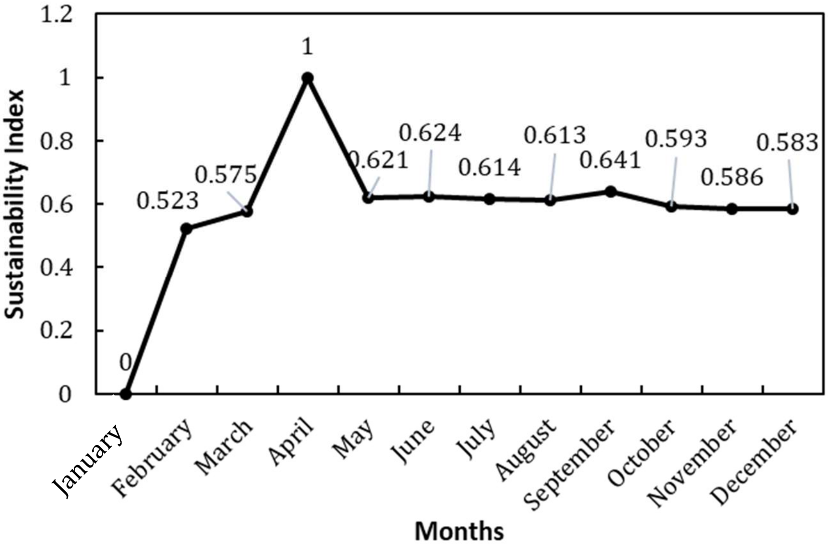

Figure 1. Tren sustainability index

The Sustainability Index shows a fluctuating pattern over the observed months. It increases from February (0.523) to April (1.000), then declines through May (0.621) and reaches stability wth very litthe fluctuations until December means the efficiency starts to be controlled.

Results of the SOTE Method

The application of the Sustainable Overall Throughput Effectiveness (SOTE) method was carried out to evaluate production performance by integrating machine operational effectiveness (OEE) and environmental sustainability performance represented by the Sustainability Index (S). This approach provides a more comprehensive evaluation than conventional OEE because it not only assesses productivity, but also considers the efficiency of resource utilization and environmental impact. The output of monthly SOTE shown on Table 9.

The SOTE calculation results show fluctuations in operational sustainability performance throughout the observation period. The lowest SOTE value occurred in January, which was zero, reflecting the worst sustainability condition due to the low sustainability index despite the relatively high OEE value. The movement each months shown on Figure 2.

Table 9. SOTE calculation results every month

Month	SOTE (monthly)
January	0.000
February	45.745
March	46.418
April	76.200
May	52.737
June	48.145
July	50.857
August	51.252
September	52.518
October	50.118
November	49.935
December	50.126

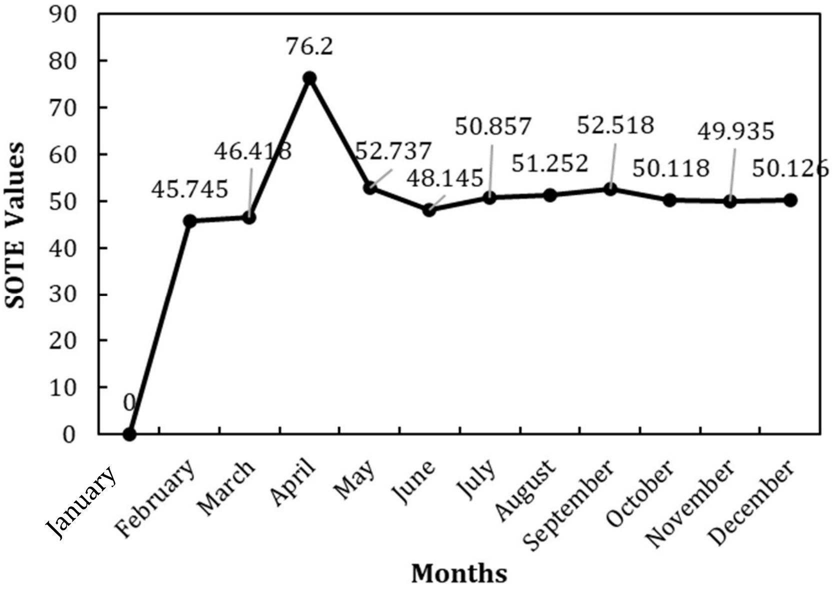

Figure 2. Tren sustainable overall throughput effectiveness

The results of the monthly SOTE evaluation show that operational sustainability performance is significantly influenced by the alignment between energy consumption and production output. In some periods, increased throughput was not followed by an increase in the SOTE value, which indicates that energy efficiency has not been achieved even though production performance is technically optimal. Conversely, when energy consumption is more proportional to the output volume, the SOTE value increases.

Monthly SOTE results demonstrate a dynamic pattern with notable variations throughout the year. The index reaches its lowest value in January and gradually improves toward a maximum in April, before slightly declining and stabilizing in the later months. These findings indicate that sustainability oriented effectiveness is not constant over time, but varies across operational periods, highlighting the importance of continuous monitoring and evaluation of sustainability performance.

Using annual SOTE calculation the results value is 48.5 which indicates a moderate level of operational sustainability, meaning that production effectiveness has been achieved, but the integration of energy efficiency and environmental sustainability has not yet been consistently optimized. To provide a more detailed comparison between OEE and SOTE, the results are presented in Table 10.

Table 10. Comparation between monthly SOTE with monthly OEE

Month	OEE	SOTE (monthly)
January	96.7	0.000
February	87.4	45.745
March	80.7	46.418
April	76.2	76.200
May	84.9	52.737
June	77.1	48.145
July	82.8	50.857
August	83.6	51.252
September	81.9	52.518
October	84.5	50.118
November	85.2	49.935
December	86.0	50.126

Table 11. Comparation between SOTE 2024 with SOTE 2025

Month	SOTE (monthly) 2024	SOTE (monthly) 2025
January	22.511	0.000
February	33.655	45.745
March	26.957	46.418
April	26.674	76.200
May	34.248	52.737
June	29.900	48.145
July	29.142	50.857
August	87.100	51.252
September	61.689	52.518
October	0.000	50.118
November	44.769	49.935
December	30.316	50.126

The comparison between Overall Equipment Effectiveness (OEE) and Sustainable Operational and Technical Efficiency (SOTE) reveals fundamental differences in production performance evaluation. The results indicate that periods with high OEE values may still exhibit low SOTE scores when energy consumption or resource intensity is relatively high compared to other periods. This demonstrates that SOTE evaluates not only technical effectiveness but also the balance between productivity and energy efficiency. During the observation period, OEE ranged from 76.2% to 96.7% and remained relatively stable above 80%, indicating effective machine performance in terms of availability, performance, and quality. However, SOTE showed wider variation, ranging from 0.000 to 76.200, highlighting its greater sensitivity in detecting inefficiencies not captured by OEE. A deeper analysis is required to compare the 2024 data, when the company had not yet implemented the EMAS method, with the 2025 data in order to assess the impact of EMAS on energy usage. The comparison is presented in Table 11.

The annual SOTE increased from 36.5% in 2024 to 48.5% in 2025, indicating improved energy efficiency performance following the implementation of the Energy Management System (EMAS). In 2024, SOTE values showed high variability, ranging from 0.000 to 87.100, reflecting inconsistent energy efficiency and operational control prior to EMAS adoption. In contrast, the 2025 SOTE distribution became more stable, mostly ranging between 45 and 52, indicating improved consistency and integration of energy management into production processes. This reduction in variability suggests enhanced operational control and more consistent implementation of energy efficiency strategies. The regression model uses data from 2024 and 2025 to compare conditions before and after the implementation of the EMAS method, as shown below:

$$SOTE = -121.9 \times 0.64(Output) \times 12.26(EMAS) \tag{11}$$

Regression analysis further indicates that output has a positive coefficient of 0.64, demonstrating its significant role in improving SOTE. Meanwhile, EMAS shows a positive coefficient of 12.26, suggesting a potential contribution to SOTE improvement, although its statistical significance is limited. Overall, these findings indicate that EMAS contributes to improved stability and performance of sustainable operational efficiency, while output remains the primary determinant of SOTE.

CONCLUSIONS

Based on the results of the case study at Company XYZ, several conclusions can be drawn as follows:

1. **Integration of EMAS and SOTE Forms a Strong Framework**
   The integration provides an enhanced framework that offers a more comprehensive perspectiveby aligning environmental management and operational performance. EMAS provides a systematic guide to identifying resource waste, while SOTE quantifies the impact of this waste on production effectiveness in a comprehensive and easy to understand indicator.
2. **SOTE Provides a More Realistic Picture Than OEE**
   This study proves that conventional OEE can provide an overly optimistic picture because it does not take into account resource consumption. By including the Sustainability Index, SOTE is able to reveal the actual performance vulnerabilities and provide a strong data based foundation to support investment in energy efficiency.
3. **This Approach Supports the Achievement of Dual Goals**
   The applied framework allows companies to increase productivity and profitability through reduced operational costs, while also achieving sustainability targets and compliance with regulations, such as Presidential Instruction Number 13 of 2011 and SDGs [6], [7]. This approach reflects the application of the triple bottom line concept (planet, people, profit) in the manufacturing context.
4. **Applicability for Industries in Developing Countries**
   This case study shows that the integrated EMAS-SOTE approach is practical and can be applied by manufacturing industries in Indonesia and other developing countries. Its implementation does not always require high tech investment on a large scale, but can be started through structured management audits and gradual operational improvements.

Recommendations for Further Implementation:

1. Manufacturing companies are advised to adopt the integrated EMAS-SOTE approach as part of their performance management system.
2. Comprehensive socialization and training are imperative to ensure that all organizational echelons, from frontline operators to management, possess the necessary understanding to contribute to continuous improvement initiatives.

3. Future research should consider expanding the Sustainability Index (S) in the SOTE framework by incorporating additional metrics, such as carbon emissions and solid waste generation, to facilitate a more comprehensive and holistic environmental evaluation.

Thus, the integration of EMAS and SOTE has proven to function not only as a diagnostic tool, but also as a strategic framework for transforming sustainability challenges into measurable opportunities in improving operational competitiveness.

ACKNOWLEDGEMENTS

DECLARATION OF CONFLICTING INTERESTS

The authors declare that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this article.

FUNDING

Nomenclature

AC = Air Conditioner
A = Availability
B3 = Hazardous and Toxic Materials *(implicit in environmental & EMAS context)*
DJSI = Dow Jones Sustainability Index
E = Environmental
EMAS = Eco Management and Audit Scheme
ERP = Enterprise Resource Planning
ESD M = Energy and Mineral Resources
ESG = Environmental, Social, and Governance
G = Governance
H2O = Water (two hydrogen atoms and one oxygen atom)
IEA = International Energy Agency
IPA = Water Treatment Installation
IPCC = Intergovernmental Panel on Climate Change
IRENA = International Renewable Energy Agency
ISO = International Organization for Standardization
IoT = Internet of Things
KPI = Key Performance Indicator
MTBF = Mean Time Between Failure
MTTR = Mean Time To Repair
OEE = Overall Equipment Effectiveness
P = Performance
PAM = Drinking Water Company
PDCA = Plan - Do - Check - Act
PLC = Programmable Logic Controller
PT = Limited Liability Company
Q = Quality
QC = Quality Control
REN21 = Renewable Energy Policy Network for the 21st Century
R&D = Research and Development
RUEN = National Energy General Plan
S = Sustainability Index
SDGs = Sustainable Development Goals

SI = Sustainability Index
SPAM = Drinking Water Supply System
SOTE = Sustainable Overall Throughput Effectiveness *(in some parts written: Sustainable Overall Throughputability Effectiveness)*
UNDP = United Nations Development Programme
WCED = World Commission on Environment and Development

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