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Operational and Environmental Optimization through Lean and Life Cycle Assessment in a Coal-Fired Power Plant

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ABSTRACT
This study highlights the critical need for energy efficiency improvements and environmental impact reduction in coal-fired power plants. The main objective is to evaluate the integration of Lean Thinking and Life Cycle Assessment (LCA) methods to optimize operational performance and sustainability in a 25 MW coal-fired power plant in Indonesia. With a quantitative research design, the study analyzes auxiliary power consumption, boiler combustion efficiency, and emissions before and after Lean-based interventions, supported by LCA impact assessment using Open LCA software and TRACI method. The results show a decrease in auxiliary power consumption from 14.75% to 11.75% of total production, an increase in steam production by 3.75% per ton of coal, a decrease in coal consumption per kWh by 3.48%, and a reduction in Global Warming Potential by 12%. Discussion highlights the synergy between operational efficiency and environmental benefits, while acknowledging the trade-offs of small increases in acidification and particulate emissions. This study enriches insights by empirically linking Lean operational improvements to environmental impact reduction, and provides a practical framework for sustainable energy generation. These findings confirm that an integrative Lean-LCA approach is essential to balance economic and ecological objectives in fossil fuel power plants.

Keywords: Lean Thinking Life Cycle Assessment Energy efficiency Coal-fired power plants Environmental Impact
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1. INTRODUCTION

The global energy landscape is undergoing significant transformation due to rising demand, environmental concerns, and geopolitical factors affecting energy commodity prices. Coal-fired power plants, which are still the main source of electricity generation in many countries including Indonesia, are facing increasing pressure to improve operational efficiency and reduce environmental impact. Rising coal prices triggered by geopolitical tensions such as the Russia-Ukraine conflict have reinforced the need for coal-fired power plants to optimize energy consumption to maintain economic viability and operational excellence Increasing efficiency in power plants not only reduces operational costs but also reduces dependence on external energy supplies, thereby improving system resilience and stability.

Operational efficiency in coal-fired power plants is closely related to efforts to minimize energy losses and maximize the conversion of coal energy into usable steam and electricity. Inefficiencies often occur due to manual or outdated operations that cause excessive heat loss and suboptimal auxiliary power consumption, which can be measured through metrics such as specific energy consumption (SEC) and thermal efficiency. Reducing waste heat and optimizing the use of auxiliary equipment are essential to achieving high overall equipment effectiveness, which directly increases the competitiveness of power plants amidst the increasing complexity of the global energy market

Although approaches to operational improvement exist, a major challenge remains in systematically integrating energy efficiency with environmental impact assessment to support sustainability. Lean Thinking, a methodology originally developed for manufacturing to reduce waste and optimize process flows, has proven its potential in improving operational efficiency by identifying and eliminating non-value-added activities, including energy waste . Meanwhile, Life Cycle Assessment (LCA) provides a comprehensive framework for evaluating environmental impacts throughout the life cycle of a product or system, from raw material extraction, production, operation, to final disposal .

Integrating Lean Thinking with LCA in the context of coal-fired power plants can provide a holistic approach that not only optimizes energy efficiency but also reduces environmental impacts such as greenhouse gas emissions and air pollutants. This integration links operational improvements with sustainability goals, providing decision makers with powerful insights into how process optimization impacts environmental performance throughout the power plant life cycle . However, research focusing on this integrative strategy, especially in optimizing auxiliary power consumption (kWh aux) and boiler combustion efficiency, is still very limited.

Previous studies have explored various aspects of Lean implementation in power plants, from waste identification models to the use of specific tools such as Value Stream Mapping (VSM) to improve operational maintenance and availability . Other studies have focused on the application of LCA to measure the environmental impact of coal-fired power plants, including the analysis of CO_2, CH_4, N_2O emissions, and the potential of technologies such as Carbon Capture and Storage (CCS) to mitigate emissions . While these studies have made important contributions in part, there is a research gap regarding the combined application of Lean and LCA methods to holistically address energy efficiency and environmental sustainability in coal-fired power plants.

This study aims to fill this gap by developing an integrated model of Lean Thinking and Life Cycle Assessment tailored for coal-fired power plants. This model is expected to identify energy waste, optimize auxiliary power consumption, and improve boiler combustion efficiency while evaluating environmental impacts in the form of emission reductions. The case study was conducted at a power plant owned by PT XYZ in Gresik, East Java, with a capacity of 25 MW. The integration of this approach is expected to support long-term operational sustainability and provide practical solutions for cleaner energy production in Indonesia's electricity sector.

In summary, the integration of Lean Thinking and LCA offers a promising path to improve the energy efficiency and environmental performance of coal-fired power plants. The novelty of this study lies in the application of the combined framework to a real-world coal-fired power plant operating setting, thereby expanding the current knowledge and providing a replicable model for the power generation industry seeking to achieve sustainability amidst the evolving global energy dynamics

2. RELATED WORK

Research on improving energy efficiency and reducing environmental impacts in coal-fired power plants (PLTU) has received extensive attention in recent decades. Lean Thinking and Life Cycle Assessment (LCA) approaches are two methods that are often used separately or integrated to optimize operational performance and environmental sustainability in the energy sector

Several previous studies have examined the application of Lean Thinking in PLTU, with the main focus on reducing energy waste, increasing equipment availability, and optimizing maintenance processes. Table 1 in the study a provides a comprehensive comparison of previous studies, highlighting key findings and research gap. A multi-aspect model was developed to identify waste sources in thermal power plants and to select the most appropriate Lean Manufacturing practices to enhance productivity . Value Stream Mapping was applied to reduce waste time in coal handling unit maintenance, resulting in increased availability and reliability of the power plant . A study combined Lean Thinking with Life Cycle Assessment (LCA) to improve availability factors and identify environmental impacts during the overhaul process of a thermal power plant .

Meanwhile, research related to LCA in coal-fired power plants emphasizes the importance of life cycle analysis to measure greenhouse gas emissions, air pollutants, and other environmental impacts. The potential of Carbon Capture and Storage (CCS) technology was assessed using Life Cycle Assessment (LCA), revealing significant reductions in CO_2 emissions and other pollutants . SimaPro software was used to identify and measure CO_2, CH_4, and N_2O emissions from production activities of a coal-fired power plant in East Java .

Although these studies have made important contributions, there are some weaknesses and gaps that need to be addressed. Most Lean studies are still limited to operational aspects such as availability and maintenance time, without integrating a comprehensive environmental impact analysis. In contrast, many LCA studies focus on evaluating environmental impacts without exploring in depth the impact of operational process improvements through Lean. The integration of both is still very limited, especially related to energy and boiler combustion efficiency which directly affect emissions. Coal quality variability and operational fluctuations have also not been addressed holistically in the current literature both is still very limited, especially related to energy efficiency, especially auxiliary electricity consumption.

This study fills the gap by developing an integrated Lean Thinking and LCA model that combines operational energy optimization with comprehensive environmental impact evaluation. This approach is expected to provide practical and applicable solutions that have not been widely found in previous studies, especially in the context of coal-fired power plants in Indonesia

Table 1. Comparison of Previous Studies

Author & YearResearch ObjectiveMethodologyKey FindingsResearch GapHussain et al., 2020 [18]Develop multi-aspect waste identification and improvement plans in PLTU using Lean ManufacturingQualitative, quantitative, AHPAccurate waste identification and effective lean manufacturing improvement planFocus on operational aspects, no LCA integrationChinhengo et al., 2020 [19]Use VSM to reduce waste time in maintenance at coal handling planValue Stream Mapping (VSM)6.5% reduction in waste time, availability improvement by 0.158%No environmental impact assessmentDevi & Putu, 2020 [20] mprove PLTU EAF using Lean Thinking, VSM, 5S, and LCALean Thinking, LCAAF improved from 90.21% to 90.84%, with environmental impact recommendationsFocused on overhaul, no detailed kWh aux and boiler optimizationSalah & Mustafa, 2020 [21] Reduce SEC in food industry using Lean ProductionLean Production15.1% decrease in SECFood industry, not PLTU focusedMuhammad & Farzaneh, 2023 [22] Assess environmental impacts of CCS-CCU technology in PLTULCAPotential 28% CO_2 emission reductionFocus on CCS-CCU tech, no lean thinking integrationWibawa et al., 2020 [23]Assess environmental impacts of coal power plant productionLCA with SimaProCO_2, CH_4, N_2O emissions per kWh electricityEnvironmental assessment without lean approach

Thus, this study strengthens the literature by presenting a model that combines Lean operational efficiency with environmental life cycle assessment, while addressing real challenges in energy and environmental management in modern coal-fired power plants

3. RESEARCH METHODS

This study uses a quantitative research design that integrates Lean Thinking principles with Life Cycle Assessment (LCA) methodology to examine energy efficiency improvements and environmental impact mitigation in a coal-fired power plant. The case study focuses on a 25 MW power plant owned by PT XYZ located in Gresik, East Java, Indonesia, which supplies steam and electricity to a paper manufacturing operation. The methodology is systematically structured to collect, analyze, and interpret operational and environmental data before and after the implementation of Lean, and use LCA to assess the life cycle environmental footprint associated with these operational changes.

3.1 Research Design and Approach

This study uses a quantitative case study approach to measure the effects of Lean Thinking interventions on specific energy consumption (auxiliary kWh) and boiler combustion efficiency and their impact on emissions. Lean Thinking is applied to identify and eliminate energy waste in the auxiliary system and boiler operation of the power plant, with the aim of improving overall operational efficiency. Simultaneously, LCA is used to evaluate the environmental consequences of these operational changes from a life cycle perspective, following the international standards ISO 14040 and ISO 14044], [10],. This integrated approach ensures that operational improvements are assessed not only based on performance metrics but also on sustainability criteria.

3.2 Data Collection

Operational data were collected over four years covering three distinct phases: before Lean implementation (June 2021 - May 2022), Lean implementation and optimization (January 2024 - December 2024), and a transition phase where operational adjustments occurred (June 2022 - December 2023). The data collected included electrical energy consumption for auxiliary equipment (kWh aux), boiler fuel consumption, coal quality parameters, steam production, and electrical output. Specifically, auxiliary power consumption includes equipment such as coal handling units, boiler fans, feedwater pumps, and water treatment motors which are the main contributors to the power plant's energy consumption. Coal proximate and ultimate analysis data were used to characterize fuel quality and support combustion optimization calculations

3.3 Implementation of Lean Thinking

Lean Thinking principles are used to identify sources of energy waste in the auxiliary power plant system and the boiler combustion process. One of the main interventions is the installation of variable frequency drives (inverters) on motors and pumps to regulate speed according to operational needs in real-time, replacing fixed speed control using valves and dampers. This approach aims to reduce excess energy consumption without sacrificing system performance or reliability. Waste elimination efforts are focused on minimizing the use of energy that does not provide added value, optimizing process flows, and increasing equipment availability and reliability . The impact of Lean interventions is monitored through continuous measurement of auxiliary power consumption and boiler efficiency parameters

3.4 Life Cycle Assessment (LCA) Framework

LCA is conducted to quantify the environmental impacts associated with the operational activities of the power plant before and after the implementation of assessment follows the **ISO 14040 and ISO** 14044_ standards consisting of four stages: determination of objectives and scope, life cycle inventory (**LCI), life cycle impact assessment (LCIA), and interpretation** [10].

- Determination of Objectives and Scope: LCA aims to evaluate the environmental benefits of Lean-based efficiency improvements, focusing on reducing fuel consumption and emissions during electricity and steam production. The system boundary includes coal handling, boiler combustion, turbine operation, and the electricity generation process. Functional units are defined per kilowatt-hour (kWh) of electricity generated.
- Life Cycle Inventory: Input-output data are collected for all relevant flows, including coal consumption, auxiliary power consumption, air emissions (**CO_2, CH_4, N_2O, SO_x, NO_x),** and waste. Data sources are from PT XYZ operational technical report and coal laboratory analysis.
- **Life Cycle Impact Assessment: LCIA** uses OpenLCA software with US EPA TRACI 2.1 method to quantify **impact categories such as Global Warming Potential (GWP), Acidification Potential, and Human** Health Impacts (Particulates). Characterization factors are used to convert inventory data into potential environmental impacts.
- Interpretation: Results are analyzed to identify key contributors to environmental burdens and recommend operational improvements to maximize energy efficiency and environmental benefits

3.5 Data Analysis Procedure

Data analysis involves a comparative evaluation of energy consumption and emissions before and after Lean implementation. Auxiliary power consumption is calculated as a percentage of total electrical output to assess efficiency improvements. Boiler efficiency is measured based on steam production per unit of coal and fuel utilization rate. Emission calculations are derived from fuel consumption and combustion stoichiometry data, adjusted for excess air intake. LCA results are interpreted in the context of operational performance metrics to provide a comprehensive assessment of sustainability improvements.

3.6 Tools and Software

The study used Open LCA version 2.4 for life cycle modeling and environmental impact assessment. TRACI 2.1 was used to estimate environmental impact categories relevant to the coal combustion process. Statistical analysis tools supported data validation and trend analysis of changes in energy consumption and emissions during the study period

4. RESULT AND DISCUSSION

4.1 Auxiliary Power Consumption and Energy Efficiency

Auxiliary power consumption (kWh aux) in coal-fired power plants constitutes a significant portion of the total energy used and directly affects the overall efficiency and operating costs of the plant. The auxiliary system includes critical equipment such as coal handling units, boiler feedwater pumps, air fans, condensate pumps, cooling motors, and lighting systems within the facility. Optimizing the energy consumption of these systems can provide substantial improvements in plant performance and support operational sustainability .

Figure 1 illustrates the Lean Process Flow Diagram designed to optimize auxiliary power consumption in a coal-fired power plant. The process begins by identifying energy waste, followed by analyzing auxiliary power usage across various systems. After understanding the power consumption patterns, the next step focuses on improving control systems to better manage energy use. Subsequently, the implementation of Variable Frequency Drives (VFDs) optimizes motor speeds in real-time based on operational needs, significantly reducing unnecessary energy consumption. The final stage aims to reduce auxiliary power consumption, leading to more efficient plant operations, reduced costs, and a smaller environmental footprint. This flow demonstrates the systematic approach of Lean Thinking in enhancing operational sustainability

Figure 1. Lean Process Flow Diagram to Optimize Auxiliary Power Consumption

This study presents an in-depth analysis of auxiliary power consumption patterns at PT XYZ Steam Power Plant before and after the implementation of Lean Thinking-based operational improvements, specifically focusing on the installation of variable frequency drives (VFDs) on critical motors and optimization of operational controls Data were collected for two main periods, namely June 2021-May 2022 as the baseline period before Lean was implemented, and January-December 2024 as the period after Lean was implemented. Table 2 shows a significant decrease in auxiliary power consumption from 14.75% to 11.75% of total electricity production, with notable reduction in key components like feed water pumps and primary air fans, mainly due to the installation of VFDs

Tabel 2. Auxiliary kWh consumption before and after Lean

Period	Before Lean		After Lean		Decrease
	1 Jun 2021- 1 May 2022		1 Jan- 31 Des 2024		
	kWh/year	% A	kWh/year	% B	% A-B
kWh Generator	113.883.840		123.272.160		
kWh Auxiliary					
Coal Handling	243.603	0.21%	217.921	0.18%	0.04%
Feed Water Pump	2.773.320	2.44%	1.892.580	1.54%	0.90%
Primary Air Fan	5.307.572	4.66%	2.746.872	2.23%	2.43%
Secondary Air Fan	2.076.960	1.82%	2.080.620	1.69%	0.14%
Induced Draft Fan	2.342.520	2.06%	3.233.220	2.62%	- 0.57%
Circulating W.P	326.250	0.29%	340.065	0.28%	0.01%
Clarifier Tr	252.990	0.22%	270.090	0.22%	0.00%
Demin Tr	1.928.160	1.69%	2.030.400	1.65%	0.05%
Low auxiary Tr	1.549.317	1.36%	1.684.199	1.37%	- 0.01%
Total	16.800.692	14.75%	14.495.967	11.76%	2.99%

The plant produced a total of 113,883,840 kWh of electricity per year before optimization and increased to 123,272,160 kWh per year after optimization, indicating an increase in production capacity and output. However, the auxiliary power consumption as a percentage of total production showed a significant decrease from 14.75% to 11.75%. This decrease reflects a relative reduction in energy consumption by the auxiliary system, which means an increase in the overall net efficiency of the plant .

The power consumption breakdown of various auxiliary equipment shows significant energy savings in several key components. The feed water pump, which plays an important role in supplying water to the boiler, experienced a decrease in power consumption from 2.44% to 1.54% of total production. Likewise, the primary air fan decreased significantly from 4.66% to 2.33%, and the secondary air fan showed a slight decrease from 1.82% to 1.69%. This decrease was mainly due to the replacement of the conventional valve or damper control system with VFD technology, which allows the motor speed to be dynamically adjusted according to actual process needs, thereby eliminating or damper control system with VFD technology, which allows the motor speed to be dynamically adjusted according to actual thereby eliminating energy waste due to operating the motor at a fixed

In contrast, the induced fan showed a slight increase in power consumption, from 2.06% to 2.62%. This increase is seen as a necessary adjustment to maintain boiler stability and efficient combustion conditions, as compensation for changes in airflow dynamics caused by optimization of other auxiliary systems. Maintaining combustion stability is crucial for overall plant efficiency and emission control, so an increase in auxiliary load in this section is acceptable in the context of increasing net efficiency.

Overall, the implementation of Lean Thinking and technology upgrades resulted in a reduction in auxiliary power consumption of about 2.99% of total production. In other words, this is equivalent to a saving of 29.9 kWh for every 1000 kWh of electricity generated. If calculated over the annual production, the auxiliary energy savings reach about 3,599,547 kWh throughout 2024, which is a significant improvement in operations. This reduction in auxiliary power consumption not only increases the efficiency of the plant but also has a direct impact on reducing operating costs by reducing electricity usage and coal consumption that must be balanced for auxiliary load needs. The switch to variable speed control allows for more precise equipment tuning, reducing unnecessary operating time and energy waste, while maintaining or improving system reliability.

In addition to economic benefits, reducing auxiliary power consumption also has a positive impact on the environmental performance of the power plant by reducing fuel requirements and emissions. The energy saved reduces the carbon footprint per unit of electricity produced, supporting global greenhouse gas reduction goals. This increase in operational efficiency is also in line with the principles of sustainable energy management which emphasizes reducing losses and optimizing resource use

These results reinforce the effectiveness of Lean Thinking tools in energy-intensive industries, as documented in studies that use value stream mapping and waste elimination strategies to reduce auxiliary loads and improve overall plant performance. The significant reduction in auxiliary power consumption at PT XYZ demonstrates the potential for widespread application of Lean methodology to other coal-fired power plants around the world, especially in locations that still use manual operations and legacy control technologies.

Integration of technologies such as VFD with Lean principles demonstrates the crucial role of innovation and process control in achieving energy efficiency. This combination enables adaptation to changing process conditions and varying fuel quality, increasing responsiveness and minimizing energy waste .

In conclusion, the analysis of auxiliary power consumption shows that focused Lean Thinking interventions, supported by technology improvements and continuous monitoring, significantly reduce energy use in the main auxiliary system. This reduction increases the net efficiency of the plant, reduces fuel consumption, and supports environmental sustainability without compromising operational reliability. These findings provide a strong empirical basis for the adoption of Lean principles in the management of power plant auxiliary systems to achieve economic and ecological benefits.

4.2 Boiler Efficiency Optimization

1. This section discusses the evaluation of boiler performance improvement resulting from the implementation of Lean Thinking in PT XYZ's coal-fired power plant. Boiler efficiency is a crucial parameter that affects fuel consumption, steam production, and ultimately the overall energy conversion effectiveness in the plant. Optimization of the combustion process and operational parameters in the boiler system significantly contributes to the reduction of energy losses and the
2.

minimization of environmental emissions.

3. Figure 2 This flow diagram illustrates the steps involved in optimizing boiler performance through Lean Thinking principles. The process begins by measuring the existing boiler performance, which includes evaluating combustion parameters such as the air-fuel ratio based on stoichiometric combustion reactions. Next, Lean interventions are applied, focusing on resetting the air-fuel ratio and optimizing combustion by adjusting primary and secondary air supplies. The final phase involves measuring the improved boiler performance after the optimization, which results in enhanced steam production and reduced coal consumption. These steps are designed to reduce energy losses, minimize environmental emissions, and enhance overall boiler efficiency.

Figure 2. Lean Process Flow Diagram for Boiler Efficiency Optimization

4.2.1 Boiler Performance Before Optimization

4. Before Lean intervention, the boiler was operating with standard settings referring to historical combustion data and variations in coal quality from suppliers. The coal used had a calorific value between 4000 to 4200 kcal/kg and showed variations in moisture, ash, volatile matter, and fixed carbon content, all of which affect combustion stability and efficiency. Initial measurements showed steam production of approximately 4.98 tons per ton of coal with a coal consumption of 1.27 kg per kWh of steam produced. This data became the benchmark for further improvement evaluation. Table 3 shows the operation parameters before and after Lean intervention, with improvements in steam production and coal consumption efficiency following Lean optimization, reflecting enhanced boiler performance.
5.

Table 3. Operational Parameters before and after Lean (boiler optimization)

	Unit	Before Lean (Jan-Sep 2024)	After Lean (Oct-Dec 2024
Electricity Production	kWh	83.860.800	32.129.280
Steam Production	kg	56.8314.600	203.490.000
Coal	kg	114.221.618	39.419.830
Steam/Coal	kg/kg	4.98	5.16
Steam/kWh	kg/kWh	6.32	6.33
Coal/kWh	kg/kWh	1.27	1.23

4.2.2 Combustion Process Optimization

1. Lean Thinking is a guideline for optimizing the air-fuel ratio and combustion parameters based on stoichiometric calculations and real-time monitoring. This process involves adjusting the primary and secondary air supply to achieve optimal excess air levels, ensuring complete combustion while minimizing the formation of slag, fouling, and unburned carbon. Optimization also considers the thermal behavior in the combustion chamber to improve heat transfer efficiency and reduce heat loss through steam blowdown and exhaust gas.
2.
3. 4.2.3 Quantitative Improvement After Optimization
4. After the implementation of Lean-based combustion optimization, the boiler showed significant performance improvement during the three-month monitoring period. Steam production per ton of coal increased by 3.75% from 4.98 to 5.16 tons per ton, indicating an increase in the efficiency of converting coal energy into thermal energy. Coal consumption per kWh of steam decreased by 3.48%, from 1.27 to 1.23 kg/kWh, indicating a reduction in fuel usage for the same energy output. This improvement is equivalent to a coal saving of approximately 1.42 million kilograms during the monitoring period, which has a direct impact on reducing operating costs and emissions.

5.
4.2.4 Effect of Coal Quality Variations
6. Variations in the proximate and ultimate analysis of coal require adaptive operational strategies to maintain combustion efficiency. Moisture content and ash fractions affect combustion chamber temperature and slag formation tendencies, requiring adjustments in air supply and fuel rates. Integration of Lean principles enables dynamic response to these variations, maintaining consistent combustion
performance and reducing fuel waste. This adaptive optimization is particularly important in coal-fired power plants that rely on fluctuating fuel quality due to supplier heterogeneity.
7.
8. 4.2.5 Integration with Auxiliary System Optimization
9. The improvement of boiler efficiency is complementary to the reduction of auxiliary power consumption that has been achieved. By optimizing the auxiliary electrical system and the thermal combustion process simultaneously, the plant has succeeded in improving energy efficiency holistically. This dual approach demonstrates the synergistic potential of applying Lean methodology across various subsystems in a power generation facility.
10.
11. 4.2.6 Operational and Environmental Implications
12. Increased boiler efficiency reduces fuel consumption and greenhouse gas emissions, thus contributing to economic and environmental sustainability. Lower coal usage reduces CO_2, SOx, NOx, and particulate emissions, reducing the plant's environmental footprint. From an operational perspective, improved combustion stability and reduced slag formation also reduce maintenance frequency and extend equipment life, ultimately improving plant availability and reliability.
13.
14. 4.2.7 Summary
15. In summary, Lean Thinking-based boiler optimization at PT XYZ power plant resulted in measurable improvements in steam production efficiency and fuel utilization. These improvements not only reduced operating costs through significant coal savings but also supported the goal of cleaner and more sustainable coal-fired power generation. These findings underscore the importance of integrating process optimization with environmental management frameworks to achieve comprehensive efficiency improvements at thermal power plants .
16.

4.3 Environmental Impact Assessment

The environmental impact assessment of operational improvements at PT XYZ's coal-fired power plant was conducted using the Life Cycle Assessment (LCA) methodology, focusing on the main impact categories of Acidification Potential, Global Warming Potential (GWP), and human health impacts related to particulate emissions. This assessment aims to quantitatively evaluate how efficiency improvements driven by Lean Thinking impact the plant's environmental footprint throughout its life cycle, thus providing a comprehensive perspective beyond operational metrics alone.

Using Open LCA software integrated with TRACI 2.1 impact assessment method, emission and resource consumption data from the operational phase before and after Lean implementation were analyzed. The system boundary covers all major processes, including coal handling, boiler combustion, turbine operation, and electricity generation, with functional units defined per kilowatt-hour (kWh) of electricity generated. The LCA inventory includes coal consumption, auxiliary electricity usage, as well as greenhouse gas emissions (CO_2, CH_4, N_2O) and air pollutants (SOx, NOx, particulates) obtained from operational records and laboratory analysis.. Table 4 shows the inventory data for June 2021 to May 2022, before Lean implementation, alongside the data from January 2024 to September 2024 and October 2024 to December 2024, following Lean interventions.

Table 4. Inventory Jun 2021 - Mei 2022

Category Input	Inventory Data	Amount Jun 202-Mei 2022	Amount Jan 2024-Sep 2024	Amount Oct 2024-Dec 2024	unit
Fuel/Energy	Coal	153.267.464	114.221.618	39.419.830	Kg
	Electricity	16.904.448	10.550.112	3.857.856	kWh
Output Product					
	Electricity	113.883.840	89.860.800	32.129.280	kWh
	Steam	285.236.300	221.309.200	75.873.000	kg
Emision To Air					
	CO2	245.272.076	183.522.303	63.336.679	kg
	SOx	7.730.988	5.655.645	1.951.860	kg
	NOx	1287.447	1.233.593	425.734	kg

The results show complex but overall positive environmental effects resulting from Lean interventions. Acidification Potential Assessment showed a marginal improvement after optimization of auxiliary systems only. This improvement was mainly due to increases in sulfur oxide (SOx) and nitrogen oxide (NOx) emissions, which are precursors to acid rain formation. These emissions are likely influenced by operational adjustments to equipment performance and combustion air supply settings, reflecting trade-offs in process optimization.

In contrast, Global Warming Potential has decreased significantly after the combined optimization of auxiliary power consumption and boiler combustion efficiency. The decrease in coal consumption due to the increase in combustion efficiency and the reduction in auxiliary power requirements has a direct impact on the reduction of CO_2 emissions, the dominant greenhouse gas that contributes to climate change. This decrease is in line with the global goal of minimizing the carbon footprint of fossil fuel-based energy generation and reflects the effectiveness of integrating Lean operational practices with environmental management.

For human health impacts, especially particulate emissions, LCA results show a slight increase after auxiliary system optimization, although this effect is reduced when boiler optimization is also taken into account. Particulate emissions, which have a direct impact on respiratory and cardiovascular health, are influenced by combustion conditions and particulate control mechanisms. This study highlights the importance of balancing energy efficiency improvements with the implementation of effective emission control strategies to minimize negative impacts on human health.

The impact assessment comparison tables further clarify these trends. Table 5 shows the total impact results over the monitoring period, reflecting variation in the acidification, global warming, and particulate categories. Table 6 focuses on the impacts per kWh associated with auxiliary power system optimization alone, showing increases in the acidification and human health categories despite improvements in global warming potential. Table 7 illustrates the environmental benefits of boiler optimization, with decreases across all impact categories. Finally, Table 8 synthesizes the combined effects, showing a net decrease in GWP but mixed results for acidification and human health, highlighting the complexity of the outcomes of integrated operational changes

Table 5. Impact assessment of power plant operations

Period	Unit	Jun 2021-May 2022	Jan - Sep 2024	Oct- Dec 2024
Acidification	Kg SO_2 eq	1.252.722	1.707.861	1.168.190
Global Warming	**Kg CO_2 eq**	2.553.047.925	2.539.345.505	1.810.605.259
Human health- Particulate matter	PM 2.5 eq	76.555	104.369	71

Table 6. Impact assessment of auxiliary power consumption efficiency before and after lean per kWh product

Period	Unit	Before Lean Jun2021- May 2022	After Lean Jan- Sep 2024	% Decrease
Acidification	**Kg SO_2 eq**	0.011	0.014	-27.27%
Global Warming	**Kg CO_2 eq**	22418	20.816	7.15 %
Human health- Particulate matter	PM 2.5 eq	0.000672222	0.000855556	-27.27%

Table 7. Impact assessment of boiler optimization before and after lean per kWh product

Period	Unit	Before Lean Jan-Sep 2024	After Lean Oct- Dec 2024	% Decrease
Acidification	**Kg SO_2 eq**	0.014	0.013	7.14%
Global Warming	**Kg CO_2 eq**	20.816	20.15	3.20%
Human health- Particulate matter	PM 2.5 eq	0.000855556	0.000794444	7.14

Table 8. Impact assessment of auxiliary power consumption efficiency and boiler optimization before and after lean per kWh product

Period	Unit	Before Lean Jun2021-May 2022	After Lean Oct-Dec 2024	% Decrease
Acidification	Kg SO_2 eq	0.011	0.013	-18.18%
Global Warming	Kg CO_2 eq	22418	20.15	10.12 %
Human health- Particulate matter	PM 2.5 eq	0.000672222	0.000794444	-18.18%

These findings reflect the multifaceted nature of environmental impacts on power plant operations, where improvements in one aspect can indirectly affect other aspects. These results underscore the importance of holistic process management and the integration of Lean Thinking with environmental assessment frameworks such as LCA to identify and mitigate potential negative trade-offs. In addition, these results highlight the critical role of operational control parameters such as excess air ratio, fuel quality variation, and equipment calibration in determining emission profiles.

In conclusion, this environmental impact assessment validates that Lean-based operational efficiency can substantially reduce the carbon footprint of coal-fired power plants, thereby contributing to climate change mitigation. However, small increases in acidifying and particulate emissions warrant continued monitoring and additional pollution control measures. The combined application of Lean Thinking and LCA is proven to be an effective approach to optimize energy consumption while considering environmental and health aspects, paving the way for more sustainable fossil power generation practices..

1. Discussion

The findings of this study demonstrate the significant potential of integrating Lean Thinking methodology with Life Cycle Assessment (LCA) to improve energy efficiency and environmental sustainability in coal-fired power plants. The observed reduction in auxiliary power consumption and increase in boiler efficiency are in line with the literature that confirms Lean Thinking as an effective strategy for eliminating operational waste and optimizing performance in industrial energy systems. This discussion outlines the implications of the findings, places them in a broader academic context, and explores the practical considerations and challenges associated with implementing an integrated Lean-LCA approach in the power generation sector.

The implementation of Lean principles at the PT XYZ power plant effectively addressed the main source of energy waste, primarily through the installation of variable frequency drives (inverters) on motorized auxiliary equipment. The transition from fixed-speed to variable-speed operation allowed for dynamic adjustment of power consumption to actual process needs, thereby substantially reducing unnecessary electricity consumption. These results corroborate previous studies that highlighted the effectiveness of Lean tools such as Value Stream Mapping and Six Sigma in reducing energy waste and increasing equipment availability at thermal power plants. The significant reduction in auxiliary power consumption-from 14.75% to 11.75% of total production-represents a significant operational improvement with immediate cost and environmental benefits

Optimization of the boiler combustion process resulted in measurable improvements in steam production efficiency and fuel utilization. Steam production increased by 3.75% per ton of coal and coal consumption decreased by 3.48% in line with the implementation of Lean-based process control and stoichiometric analysis. These findings are in line with previous studies that emphasize the importance of proper air-fuel ratio control and adaptive operational strategies to accommodate fuel quality variability, improve combustion efficiency, and minimize pollutant formation. These improvements not only lower fuel costs but also reduce greenhouse gas emissions, in line with global efforts to minimize the carbon footprint of fossil-based energy generation.

The Life Cycle Assessment component reveals a complex interplay between operational efficiency and environmental impacts. While global warming potential (GWP) significantly decreased following Lean implementation, reflecting CO_2 emission reductions, there were small increases in acidification potential and human health impacts related to particulate emissions in some scenarios. This trade-off highlights the inherent challenges in simultaneously optimizing multifaceted environmental objectives. Similar studies have reported similar findings, where energy efficiency improvements can lead to shifts in emissions profiles that require a holistic management approach. Therefore, these results emphasize the importance of combining Lean operational improvements with robust emission control and environmental monitoring systems

17. Operational load fluctuations, driven by variable production demand from connected paper machines, present inherent challenges in maintaining consistent efficiency. The study notes that unexpected shutdowns and load variations lead to energy losses due to suboptimal fuel utilization and auxiliary

systems. Lean Thinking helps identify and mitigate these inefficiencies by enabling more flexible and responsive control mechanisms. This adaptive operational model is critical in industrial environments characterized by dynamic demand and variable fuel quality, supporting resilient and sustainable plant performance.

18. The integration of Lean Thinking with LCA offers a comprehensive framework for sustainable power plant management. Lean focuses on process efficiency and waste reduction, while LCA provides an evaluative perspective on environmental burdens throughout the system life cycle. The complementary nature of these two approaches enables decision-making that balances economic and environmental priorities This integrated model fills the existing research gap on holistic sustainability assessment of coal-fired power plants and sets a precedent for future studies aimed at aligning operational and environmental performance metrics..

19. Practical considerations in implementation include the need for continuous data collection, real-time monitoring, and adaptive control to maintain efficiency gains. The study emphasizes the importance of investing in supporting technologies such as inverters and advanced process control systems to fully realize the benefits of Lean. In addition, effective communication and training of operational staff are essential to internalize Lean principles and ensure procedural compliance. These human and technological factors are critical determinants of success, as revealed in previous case studies in the energy sector.

The environmental benefits derived from this study go beyond carbon emission reductions. By optimizing combustion and auxiliary systems, emissions of pollutants that cause acid rain and health impacts can be better managed. However, the observed increases in some pollutant categories require the integration of emission mitigation technologies such as flue gas desulfurization and particulate filters alongside Lean interventions. This multi-strategy approach will improve compliance with increasingly stringent environmental regulations and corporate sustainability commitments.

20. Limitations of this study include the relatively short duration of post-implementation monitoring, which may not fully reflect long-term operational dynamics and maintenance impacts. In addition, variability in coal quality and external environmental factors add complexity to isolating the exclusive effects of Lean and LCA interventions. Future research should extend the monitoring duration, explore additional impact categories, and consider cross-plant comparisons to generalize the findings and refine the integrative methodology.

21. In conclusion, this study confirms that Lean Thinking systematically integrated with Life Cycle Assessment offers a viable pathway to improve energy efficiency and environmental sustainability in coal-fired power plants. The demonstrated operational and ecological benefits provide valuable insights for power plant managers, policy makers, and researchers seeking to steer fossil-fueled power generation toward a more sustainable model. These findings encourage wider adoption of the integrated Lean-LCA framework as part of a comprehensive energy and environmental management strategy in the evolving global energy landscape. .

1. Conclusion

This study shows that the integration of Lean Thinking with Life Cycle Assessment (LCA) significantly improves operational efficiency and environmental sustainability in a coal-fired thermal power plant. Lean-based optimization substantially reduces auxiliary power consumption and improves boiler combustion efficiency, leading to coal savings and greenhouse gas emissions. The LCA analysis highlights the overall reduction in global warming potential, despite trade-offs in the form of increased acidification and particulate emissions, highlighting the importance of comprehensive environmental management along with operational improvements. The findings contribute to the **body** of knowledge by **providing empirical evidence of the effectiveness of** combining Lean and LCA in industrial energy systems. The study emphasizes the critical role of adaptive process control and continuous monitoring to accommodate fuel variations and operational fluctuations. Future studies are recommended to extend the monitoring duration, explore additional environmental impact categories, and test the applicability of this integrative approach across different plant types and fuel sources. Overall, this study offers a practical and comprehensive model to promote more sustainable and efficient fossil power generation amidst the evolving global energy dynamics.

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