Process Optimization of Heating Ovens for Energy Saving and Emission Reduction in Industrial Electrodeposition Painting

Rifki Saiful[1], Satiya Cahya[2]

[1]Universitas Darma Persada, Jakarta Timur, Indonesia;
[2]Institut Teknologi Sepuluh November, Surabaya, Indonesia;

Email : rifkivanesa@gmail.com (R.S), satiyacahya@gmail.com (S.C);

Abstrak : Penelitian ini membahas upaya peningkatan sistem oven pemanas pada proses pengecatan untuk meningkatkan efisiensi energi, menekan biaya operasional, dan mengurangi emisi CO_2 tanpa mengorbankan kualitas produk. Langkah perbaikan mencakup penonaktifan unit *Recuperative Thermal Oxidizer* (RTO) guna meminimalkan konsumsi energi. Sebelum dilakukan optimalisasi, proses pemanasan terdiri dari tiga tahap (*pre-heat*, *heat-up*, dan *keep zone*) dengan total waktu sekitar 60 menit dan konsumsi LNG tahunan mencapai 230.866 m³, yang berdampak signifikan pada biaya energi dan jejak karbon. Melalui rekayasa proses, tahapan tersebut disederhanakan menjadi fase pemanasan cepat tunggal hingga suhu puncak 180°C, diikuti stabilitas pada 150°C dengan total durasi sekitar 18 menit. Redesain operasional ini berhasil memangkas waktu siklus hingga hampir 50% dan mengoptimalkan distribusi panas di dalam oven. Hasil implementasi menunjukkan penurunan konsumsi LNG lebih dari 50%, penurunan biaya energi dari Rp1,49 miliar menjadi Rp0,71 miliar per tahun, serta reduksi emisi CO_2 dari 417,87 ton menjadi 199,56 ton dalam periode dua tahun. Evaluasi kualitas mengonfirmasi bahwa perubahan proses tidak memengaruhi performa produk maupun kepatuhan terhadap standar spesifikasi. Studi ini merekomendasikan pengembangan lebih lanjut melalui optimalisasi berbasis data, integrasi sensor dan IoT untuk kendali otomatis yang presisi, serta pemanfaatan energi terbarukan sebagai bagian dari strategi manufaktur berkelanjutan.

Kata Kunci : Efisiensi Energi, Optimalisasi Oven Pemanas, Pengecatan *Electrodeposition*, Penonaktifan RTO, Manufaktur Berkelanjutan, Keberlanjutan Industri.

Abstract : *This study discusses efforts to improve the heating oven system in the painting process to increase energy efficiency, reduce operational costs, and lower CO_2 emissions without compromising product quality, including the deactivation of the Recuperative Thermal Oxidizer (RTO) to reduce energy consumption and CO_2 emissions. Prior to improvement, the heating process consisted of three separate stages—pre-heat, heat-up, and keep zone—with a total processing time of approximately 60 minutes. This configuration resulted in annual LNG consumption of 230,866 m^3, significantly impacting energy costs and the carbon footprint of the production process. Through process engineering, these stages were simplified into a single rapid-heating phase up to a peak temperature of 180°C, followed by stabilization at 150°C with a total duration of around 18 minutes. This operational redesign reduced cycle time by nearly 50% while optimizing heat distribution inside the oven. The implementation produced significant results: LNG consumption decreased by more than 50%, energy costs dropped from IDR 1.49 billion to IDR 0.71 billion per year, and total CO_2 emissions were reduced from 417.87 tons to 199.56 tons within two years. Product quality evaluation confirmed that the process changes did not affect performance or compliance with specification standards. Additionally, this study recommends further development through data-driven optimization, integration of sensors and IoT for more precise automatic control, and opportunities to utilize renewable energy as part of sustainable manufacturing strategies.*

Keywords : *Energy Efficiency, Heating Oven Optimization, Electrodeposition Painting, RTO Deactivation, Sustainable Manufacturing, Industrial Sustainability.*

---

1. Introduction

In recent years, the manufacturing industry has faced increasing pressure to reduce its environmental footprint without sacrificing production efficiency. One process that significantly contributes to energy consumption and greenhouse gas emissions is surface coating, particularly electrodeposition (ED painting), widely used in the automotive and metal industries for corrosion protection. The automotive industry consumes large amounts of energy in painting processes, especially in the Electrodeposition Painting Line (EDP) (Daniarta et al., 2022). which uses three heating oven stages: Pre-Heat, Heat-Up, and Keep Zone. Most of the energy comes from natural gas, with 50% consumed by the Recuperative Thermal Oxidizer (RTO), which reduces volatile organic compounds (VOC) and improves drying efficiency (Pu et al., 2021). Although effective for pollution control, RTOs also generate CO_2 emissions. According to PP No. 22/2021 and Ministry of Environment Regulation No. 19/2017, emissions must meet quality standards and be monitored regularly.

The objective of this activity is to reduce greenhouse gas emissions by deactivating the RTO and reducing the use of baking ovens, eliminating natural gas consumption in the process. As previously explained, natural gas consumption in the ED painting process accounts for about 69% of total energy use, equivalent to 37,771.5 tons of CO_2 in 2024. The RTO has two main functions: first, controlling air pollution from VOCs generated during paint drying (Ghobakhloo et al., 2023; Pu et al., 2021). and second, utilizing waste heat to preheat air entering the drying furnace, improving thermal efficiency. Deactivating the RTO is expected to significantly reduce natural gas consumption and CO_2 emissions without compromising product quality or regulatory compliance, supporting sustainable manufacturing (Saiful et al., 2024).

Volatile Organic Compounds (VOC) are carbon-based compounds that easily evaporate at room temperature, commonly found in paint solvents, cleaning agents, and industrial fuels. VOCs contribute

to tropospheric ozone formation and smog and pose health risks such as headaches, nervous system disorders, and long-term carcinogenic effects. Safiyo G et al. (Ghobakhloo et al., 2023) found through gas chromatography–mass spectrometry that VOC concentrations of 1.5×10^{-5} to 3.85×10^{-3} can cause cancer. Renna & Materi (2021) stated that manufacturing systems are major energy consumers and significant contributors to greenhouse gas emissions, recommending the integration of renewable energy into manufacturing energy models. Cai et al (2019) proposed the LESER (Lean Energy Saving and Emission Reduction) concept, involving steps such as clarifying actual conditions, root cause analysis, improvement, carbon emission evaluation, and standardization, achieving 10–15% energy savings. Dinesh Babu et al (2022) optimized jig design and loading patterns using 7QC tools and PDCA, reducing jig requirements from 5.8 to 4.3 per tractor, saving 30 minutes per 50 units, and improving CED line productivity without reducing quality. Bhadbhade et al (2019) analyzed energy efficiency and CO_2 reduction potential in the Swiss metals sector using a bottom-up cost curve approach. Previous studies have focused on VOC control, general energy efficiency improvements, and process optimization methods such as PDCA and LESER. However, no study has specifically examined greenhouse gas reduction through RTO deactivation and the use of a single heating oven (pre-heat) in the ED painting process in the automotive industry (Pu et al., 2021). The novelty of this research lies in developing an integrated energy efficiency and VOC control strategy without RTO (Gede Arya Rachman et al., 2025), significantly reducing natural gas consumption and CO_2 emissions while maintaining product quality and regulatory compliance.

2.   Methods

2.1   Analysis of Production Process

The electrodeposition process begins with retrieving the parts from the storage area and placing them onto the hanger (unloading part). This is followed by a pre-treatment stage to clean and prepare the surface of the parts through processes such as degreasing, rinsing, and etching(Dinesh Babu et al., 2022). Afterward, the parts undergo the coating process using the electrodeposition method, in which the coating material is applied uniformly with the assistance of an electric current (Kumar & Kumar, 2021; Singh et al., 2023). Excess coating solution is then purified through an ultrafiltration process (Fatima et al., 2024). Subsequently, the parts are dried and cured through a heating process in the baking oven, and the final step is unloading the parts from the hanger once the entire process is completed, as shown in Figure 2.1.
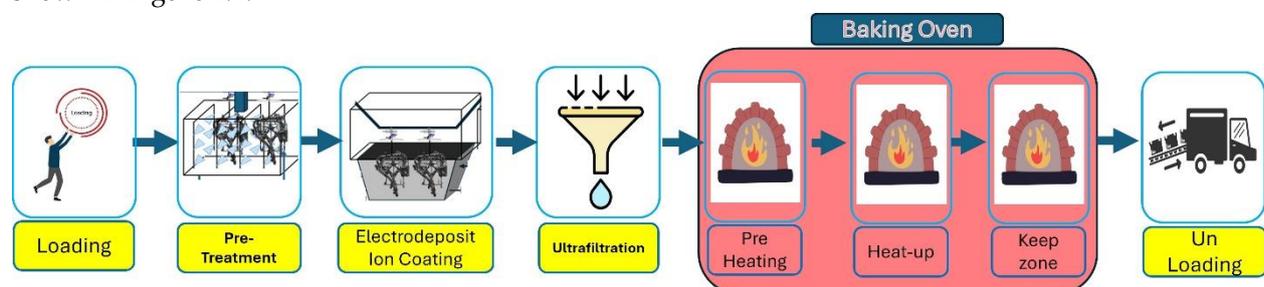

Figure 2. 1 Electro deposition process

Baking Oven Stages in the Electro Deposition Process

The heating process in the baking oven for the Electro Deposition method consists of three thermal zones, as shown in Figure 2.1, which are designed to optimize the quality of the coating layer and prevent thermal damage to the components (Pendar et al., 2022) . The first zone is the preheating
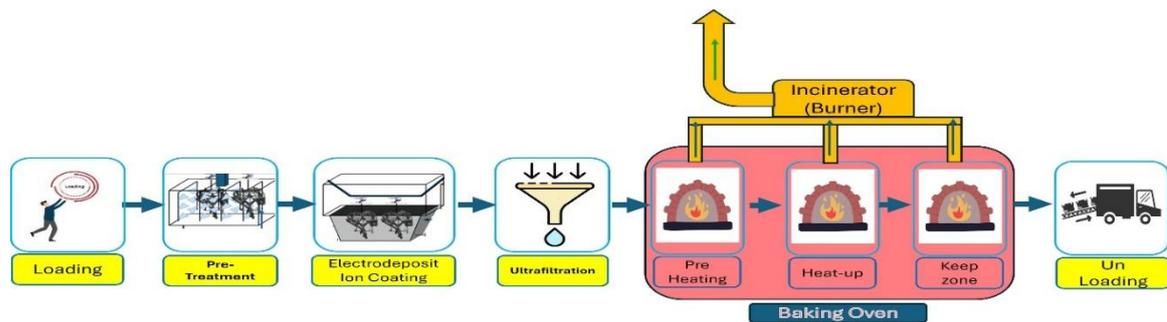
Figure 2. 2 Incenerator recuperative thermal oxidizer process

stage, where the oven is set to a temperature of 130°C. This stage serves as an initial treatment to prevent thermal shock caused by sudden temperature changes, by gradually increasing the temperature.

The second zone is the Heat-up stage, which operates within a temperature range of 165°C to 185°C. The purpose of this stage is to accelerate the attainment of the optimal working temperature required for the curing of the coating layer. The third zone is the Keep Zone, which maintains a constant temperature of approximately 165°C for a specified duration, functioning as the baking window in accordance with the standard process parameters shown in Figure 2.2. The energy used throughout this process consists of Liquefied Natural Gas (LNG), with an annual consumption of 179,539 m³, and electricity from the national utility company (PLN) amounting to 108,313 kWh per year. This high level of energy consumption indicates that the baking oven process is a highly thermal-intensive stage and requires efficient energy management to ensure operational sustainability (Saiful et al., 2024). The substantial energy demand is also driven by the operation of the incinerator, which is used to oxidize volatile organic compounds (VOC) generated during the electrodipping process. This system requires a significant heat supply to ensure complete thermal degradation of organic compounds before the exhaust gases are released into the atmosphere, as illustrated in the figure 2.2.

The main objective of this activity is to improve the heating efficiency of the baking oven by transforming the original three-stage heating process into a single integrated stage (Wu et al., 2017) and deactivating the RTO. This transformation is designed without compromising the final product quality, while maintaining critical parameters such as temperature stability, heat distribution, and coating layer integrity.

2.2   Energy Utilization Analysis

To optimize energy efficiency in the baking oven heating process, temperature measurements were carried out using a MiniTrack device as a real-time temperature data logger. The recorded temperature data were then used to calculate the thermal energy required throughout the heating process(Hamja et al., 2024). To facilitate analysis and monitoring, a table was prepared containing information on energy consumption and estimated emissions, which serves as a basis for evaluating system performance and supporting decision-making in efforts to reduce environmental impact.

Based on the data presented in Table 2.1, an identification and extraction process was conducted to obtain information related to energy consumption and emissions under various oven operating conditions. A comparative analysis was then performed between the initial condition (before the reduction of oven usage) and the condition after the implementation of the reduction measures. The purpose of this comparison is to evaluate the effectiveness of the applied energy-saving strategy and to assess its impact on reducing greenhouse gas emissions, particularly carbon dioxide (CO_2), in the Electrodeposition painting (CE painting) process (Xu et al., 2016).

2.3 Design Concept

As previously explained regarding the objective of this activity, which is to improve efficiency in the baking oven heating stage, a redesign of the Electrodeposition painting (ED painting) process flow was carried out(Sharun et al., 2022). This modification aims to simplify the heating stages from three steps into a single integrated step without reducing the quality of the final product. In addition, the new system is designed to deactivate the Recuperative Thermal Oxidizer (RTO), which was previously the largest energy consumer in the electrodipping process, by optimizing hot-air circulation and emission control systems to ensure continued compliance with environmental standards. The redesigned configuration is illustrated in Figure 2.3, showing a more efficient, integrated, and energy-saving process layout.
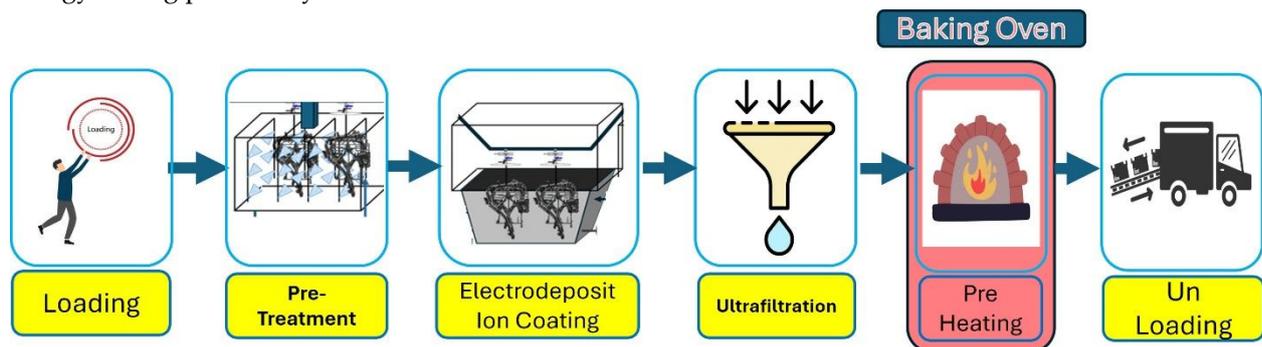

Figure 2. 3 Electrodeposition With One Step Baking Oven

In this new conceptual design, the heating process (baking oven), which previously consisted of three stages, has been simplified into two stages by eliminating the heat-up and keep-zone phases. As a compensation, the oven temperature in the initial Pre-heat stage is increased to 200–230°C. This adjustment is made to ensure compliance with the previous baking quality standards, which required a temperature of 150°C for a duration of 10–20 minutes. The modification aims to maintain the quality of the produced parts so that it remains equivalent to those processed using the conventional method, despite undergoing a more efficient sequence of stages. Table 2.1 presents the LNG consumption data prior to the implementation of the improvement activities, serving as a baseline reference for energy-efficiency analysis. This information is used as a comparison against the post-improvement results to evaluate the impact on energy savings and operational cost reduction(Chen et al., 2022).

Table 2. 1 Data LNG Consumption

Oven type	Air flow (m³/s)	Energy (kW)	LNG cons/yrs(m³)
Pre-Heat	20.06	581.50	78,502
Heat -up	11.67	465.20	65,603
Keep zone	13.33	814.10	86,761
Incenerator	80	755,95	232,897

2.4   Quality Part Guarantee

As part of the validation of the new method, we conducted a series of comprehensive tests to ensure that the components processed using this approach meet the same quality standards as those processed using the conventional method. The tests covered critical parameters such as mechanical strength, dimensional stability, corrosion resistance, and surface quality. The detailed specifications and test results are systematically presented in Table 2.2 below.

Table 2. 2 Paramater Quality Checking

Item Test	Sample				
	1	2	3	4	5
Thickness					
Hardness					
Adhesive					
Gasoline					
Oil /Acid					
Salt Spray					
Appearance					

Based on the test results for the parameters listed above and with reference to the applicable standards, it can be confirmed that the components produced through the new process design meet quality requirements equivalent to those produced using the conventional method. This validation covers conformity to technical specifications, functional performance, and overall product quality consistency.

3.   Results

In the previous process, as shown in Figure 3.1, the heating profile consisted of three main stages. The first stage was preheat at approximately 130°C for about 20 minutes, which served to reduce thermal gradients and minimize the risk of deformation in the components. Next, the Heat-Up stage was carried out by increasing the temperature significantly to 180°C for around 10 minutes to accelerate the heating of the material's core. The final stage was the Keep Zone, where the temperature was

maintained at 165°C for approximately 20 minutes to ensure uniform heat distribution and achieve the required curing conditions, thereby preserving surface quality and material strength.
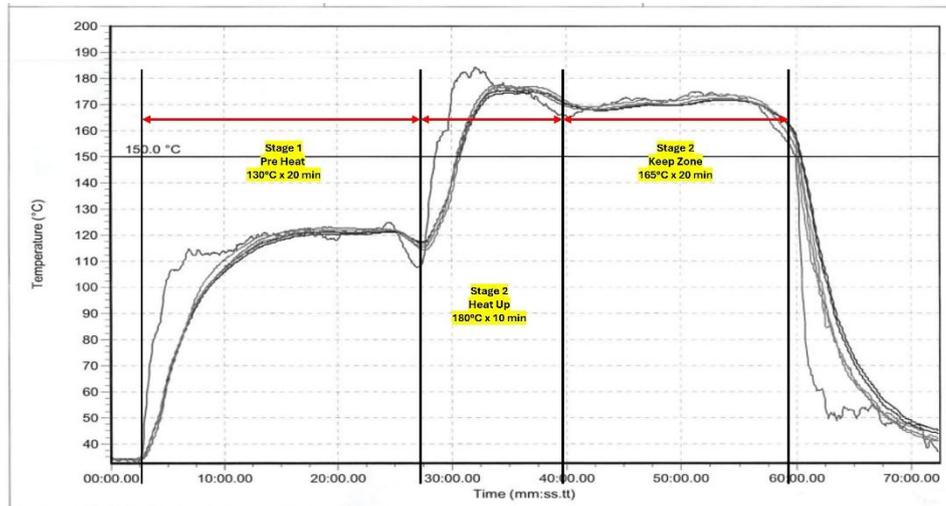

Figure 3. 1 Chart Heating All Stage

After the improvement, the heating process was carried out more efficiently by reaching a peak temperature of approximately 180°C, which was then stabilized at around 150°C to create a baking window that meets the required specifications. The components remained at 150°C for about 18 minutes, which is sufficient to achieve the curing standard without the need for the long preheating stage used previously. This modification eliminates the preheat and keep-zone stages that previously consumed significant time, resulting in a substantial reduction in total process duration and lower energy consumption, while still maintaining coating quality and material strength in accordance with technical requirements, as shown in Figure 3.2.
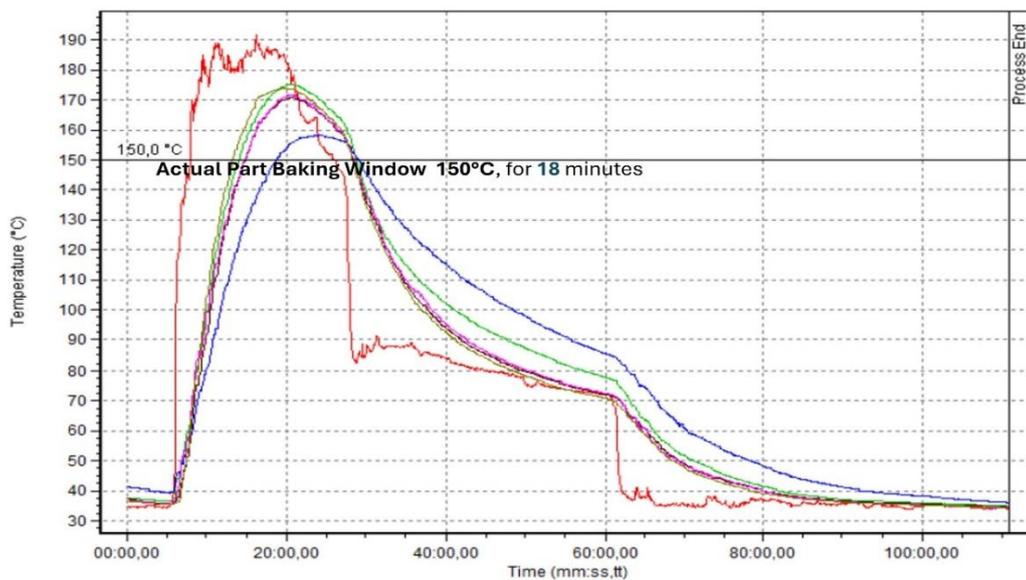

Figure 3. 2 Chart Heating One Stage

The comparison of heating profiles shows that the process prior to improvement consisted of three stages: Pre-Heat (130°C for approximately 20 minutes), Heat-Up (180°C for about 10 minutes), and Keep Zone (165°C for around 20 minutes), with a total cycle time of roughly 60 minutes. In contrast, after the improvement, the stages were simplified into a rapid heating phase up to a peak temperature of approximately 180°C, followed by stabilization at 150°C for about 18 minutes as the baking window according to the specifications. This modification eliminates the heat-up and keep-zone stages that previously required extended heating time, resulting in nearly a 50% reduction in total process duration, lower energy consumption, and maintained part quality that continues to meet curing standards.

Figure 3.3 illustrates the trend of LNG (Liquefied Natural Gas) consumption from 2023 to 2025. A significant decrease is observed each year. In 2023, LNG consumption was recorded at 230,866 m³, which then dropped to 173,116 m³ in 2024, and further declined sharply to 110,254 m³ in 2025. This reduction reflects the successful implementation of energy-efficiency programs and heating-process optimization, which reduced dependence on LNG by more than 50% within two years. The trend demonstrates t̲h̲ ̲ ̲ ̲ings and operational cost
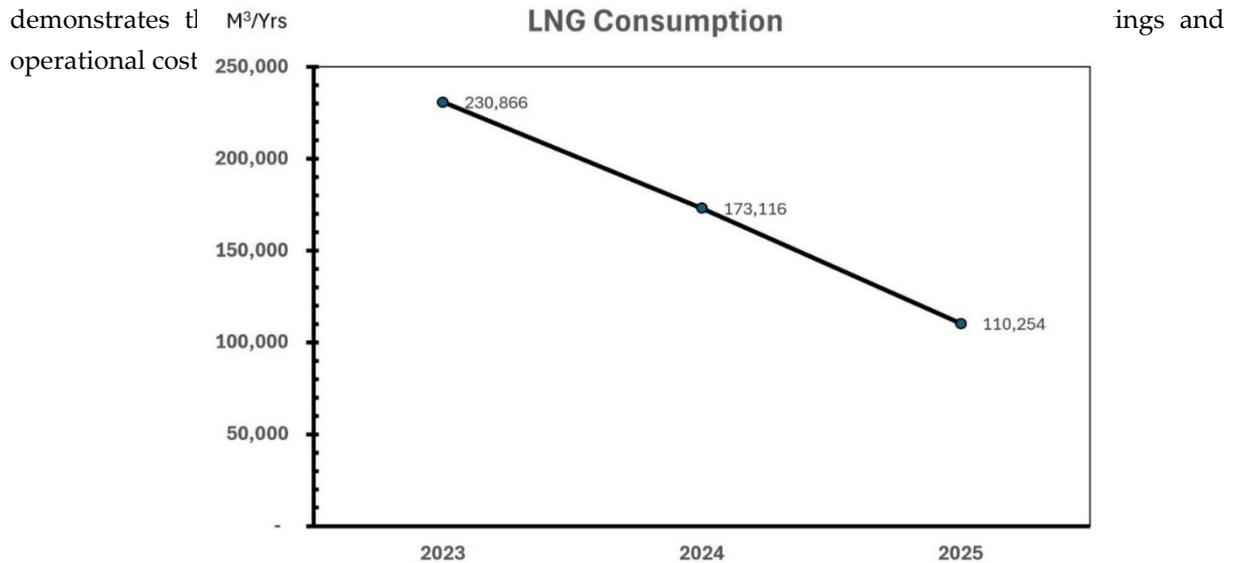

Figure 3. 3 Chart Consumption LNG

Figure 3.4 shows a decrease in energy costs (IDR) from IDR 1.49 billion in 2023 to IDR 1.12 billion in 2024, and further down to IDR 0.71 billion in 2025. This trend reflects the success of the energy-efficiency program, which significantly reduced operational costs over the past two years.
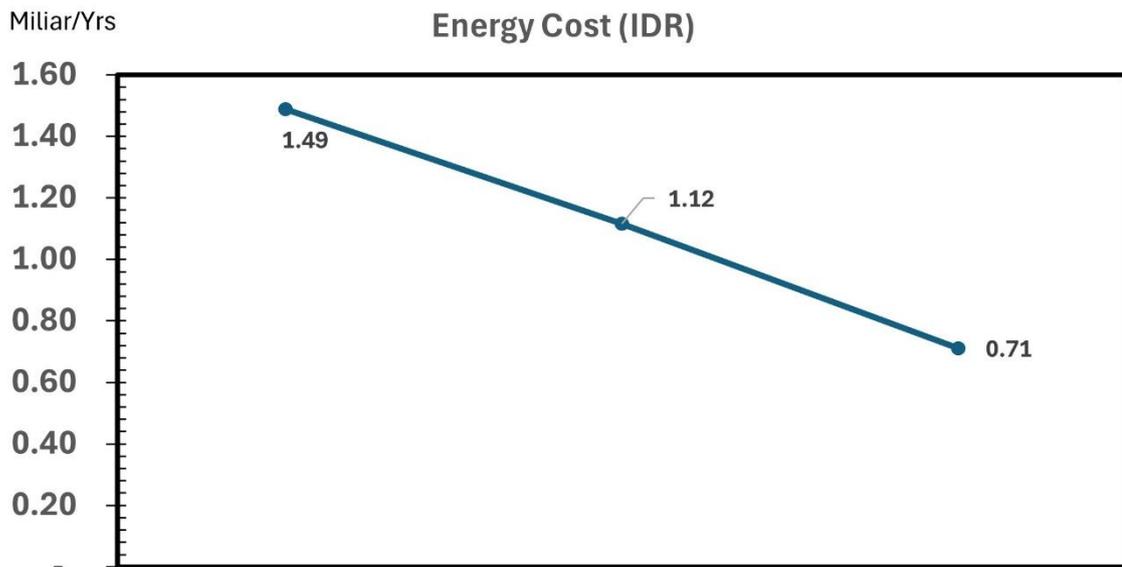
Figure 3. 4 Chart Cost Of Energy

Figure 3.5 shows a reduction in CO_2 emissions from 417.87 tons in 2023 to 313.34 tons in 2024, and further down to 199.56 tons in 2025. This trend reflects the success of the energy-efficiency program and process optimization efforts, which reduced emissions by more than 50% within two years.

Figure 3. 5 Chart Emission
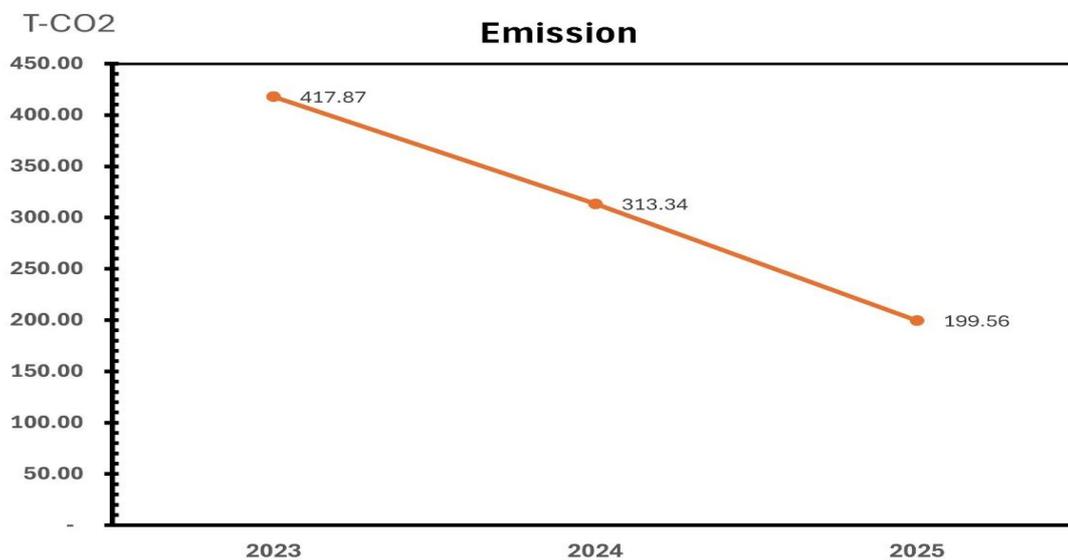
Table 3.1 presents a comparison of the oven process parameters before and after the improvement. Prior to the improvement, the three stages (Pre-Heat, Heat-Up, and Keep Zone) required an airflow of up to 20.06 m³/s and a total heating load of 1,860.8 kW, with an annual LNG consumption of 230,866 m³. After the improvement, the Heat-Up and Keep Zone stages were eliminated, resulting in

zero LNG consumption for both stages, while energy and heating were required only for the Pre-Heat stage. This change significantly reduced energy and gas usage, improving process efficiency without compromising product quality.

Table 3. 1 Comparison Of Energy Consumption Data

Oven type	Air flow (m³/s)		Energy (kW)		LNG cons/yrs(m³)	
	Before	After	Before	After	Before	After
Pre-Heat	20.06	20.06	581.50	581.50	78,502	110,254
Heat -up	11.67	0	465.20	0	65,603	0
Keep zone	13.33	0	814.10	0	86,761	0
Incenerator	80	0	755.95	0	32.897	0

As a follow-up to the process modifications, quality testing was carried out based on the parameters listed in the previous table. The test results indicate that the components produced using the new method continue to meet the established specification standards, thereby confirming that product quality remains consistent despite the modifications made to the process stages.

4. Discussion

The analysis results show that the improvement of the oven heating process has a significant impact on energy efficiency and product quality. Prior to the improvement, the process consisted of three stages with a total duration of approximately 60 minutes and an annual LNG consumption of 230,866 m³. After the improvement, the stages were simplified into a single rapid-heating phase up to 180°C, followed by stabilization at 150°C for about 18 minutes, reducing the cycle time by nearly 50% and eliminating LNG consumption for the Heat-Up and Keep Zone stages. The positive impact is evident in the reduction of LNG consumption by more than 50% within two years, the decrease in energy costs from IDR 1.49 billion to IDR 0.71 billion, and the reduction of CO_2 emissions from 417.87 tons to 199.56 tons. Quality validation confirms that components processed using the new method continue to meet specification standards, indicating that this improvement not only enhances energy and cost efficiency but also supports sustainability through significant emission reductions.

The implementation of the process modifications, which has been validated through quality testing, shows significant potential for large-scale industrial application. By reducing the heating stages and optimizing temperature parameters, this technology is capable of drastically lowering energy consumption, operational costs, and exhaust emissions (Hilmi et al., 2024)(Aigbedion et al., n.d.). At an industrial scale, the adoption of this method will enhance production line efficiency, shorten cycle times, and support sustainability through reduced LNG usage and CO_2 emissions does not require compromising product standards, making it suitable to be adopted as a best practice for efficiency-driven and environmentally conscious manufacturing industries.

Future development will focus on optimizing process parameters through data-driven approaches and thermal simulations to further improve energy efficiency(Candra et al., 2024). In addition, the integration of real-time monitoring technologies and IoT-based automatic control systems can be implemented to maintain quality consistency in large-scale production. Further studies may also

include more comprehensive environmental impact assessments, as well as the application of this method to various material types and oven configurations to expand its usability across the manufacturing sector(Steinbach et al., 2022).

As a recommendation for future research, attention may be directed toward optimizing the cooling system to maintain thermal stability, as well as integrating renewable energy sources such as solar thermal or biomass to support sustainability and reduce dependence on LNG.

5.   Conclusion

The improvement of the oven heating process successfully enhanced energy efficiency, reduced operational costs, and significantly lowered CO_2 emissions without compromising product quality. The heating stages, which previously consisted of three phases with a total duration of approximately 60 minutes and an annual LNG consumption of 230,866 m³, were simplified into a single rapid-heating phase up to 180°C followed by stabilization at 150°C for about 18 minutes, resulting in nearly a 50% reduction in cycle time. The positive impact is reflected in the reduction of LNG consumption by more than 50%, the decrease in energy costs from IDR 1.49 billion to IDR 0.71 billion, and the reduction of CO_2 emissions from 417.87 tons to 199.56 tons within two years. Quality validation confirms that the products continue to meet specification standards, making this method suitable for industrial-scale implementation to support efficiency and sustainability. Future development is directed toward data-driven optimization, IoT integration for automated control, and the utilization of renewable energy and more efficient cooling systems to expand the application of this technology across various manufacturing sectors.

References

Aigbedion, E., Ayorinde, O. B., & Adebisi, B. (n.d.). *Energy Economics and Process Optimization: A Model for Sustainable LNG Production*.

Bhadbhade, N., Zuberi, M. J. S., & Patel, M. K. (2019). A bottom-up analysis of energy efficiency improvement and CO2 emission reduction potentials for the swiss metals sector. *Energy*, *181*, 173–186. https://doi.org/10.1016/j.energy.2019.05.172

Cai, W., Lai, K. hung, Liu, C., Wei, F., Ma, M., Jia, S., Jiang, Z., & Lv, L. (2019). Promoting sustainability of manufacturing industry through the lean energy-saving and emission-reduction strategy. *Science of the Total Environment*, *665*, 23–32. https://doi.org/10.1016/j.scitotenv.2019.02.069

Candra, A., Yandri, E., Saiful, R., Uhanto, U., Hilmi, E., Hamja, N., & Ariati, R. (2024). Optimizing Compressed Air Operations for Electrical Energy Savings: A Case Study in Pharmaceutical Packaging Manufacturing. *Grimsa Journal of Science Engineering and Technology*, *2*(2), 76–86. https://doi.org/10.61975/gjset.v2i2.58

Chen, W., Fujii, M., & Sun, L. (2022). Feasibility analysis of energy system optimization for a typical manufacturing factory with environmental and economic assessments. In *Journal of Cleaner Production* (Vol. 366). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2022.132887

Daniarta, S., Kolasiński, P., & Rogosz, B. (2022). Waste Heat Recovery in Automotive Paint Shop via Organic Rankine Cycle and Thermal Energy Storage System—Selected Thermodynamic Issues. *Energies*, *15*(6). https://doi.org/10.3390/en15062239

Dinesh Babu, C., Adam Khan, M., & Uthayakumar, M. (2022). CED productivity improvement through conveyor jig density optimization. *Materials Today: Proceedings*, *52*, 246–254. https://doi.org/10.1016/j.matpr.2021.06.156

Fatima, F., Fatima, S., Du, H., & Kommalapati, R. R. (2024). An Evaluation of Microfiltration and Ultrafiltration Pretreatment on the Performance of Reverse Osmosis for Recycling Poultry Slaughterhouse Wastewater. *Separations*, *11*(4). https://doi.org/10.3390/separations11040115

Gede Arya Rachman, Rifki Saiful, Ratna Ariati, Syukri M. Nur, & Erkata Yandri. (2025). Energy Efficiency Strategy in Manufacturing Industry Through Implementation of Automation Technology. *JOURNAL OF MECHANICAL ENGINEERING MANUFACTURES MATERIALS AND ENERGY*, *9*(1), 126–139. https://doi.org/10.31289/jmemme.v9i1.13998

Ghobakhloo, S., Khoshakhlagh, A. H., Morais, S., & Mazaheri Tehrani, A. (2023). Exposure to Volatile Organic Compounds in Paint Production Plants: Levels and Potential Human Health Risks. *Toxics*, *11*(2). https://doi.org/10.3390/toxics11020111

Hamja, N., Yandri, E., Hilmi, E., Uhanto, U., & Saiful, R. (2024). Potential for Electrical Energy Savings in AC Systems by Utilizing Exhaust Heat from Outdoor Unit. *Heca Journal of Applied Sciences*, *2*(2), 64–73. https://doi.org/10.60084/hjas.v2i2.223

Hilmi, E., Yandri, E., Uhanto, U., Saiful, R., & Hamja, N. (2024). Hybrid Energy Solutions for Sustainable Offshore Oil and Gas Operations: Leveraging Thermoelectric, Solar, and Wind Potential. *Leuser Journal of Environmental Studies*, *2*(2), 52–61. https://doi.org/10.60084/ljes.v2i2.218

Kumar, S., & Kumar, R. (2021). Influence of processing conditions on the properties of thermal sprayed coating: a review. In *Surface Engineering* (Vol. 37, Number 11, pp. 1339–1372). Taylor and Francis Ltd. https://doi.org/10.1080/02670844.2021.1967024

Pendar, M. R., Rodrigues, F., Páscoa, J. C., & Lima, R. (2022). Review of coating and curing processes: Evaluation in automotive industry. In *Physics of Fluids* (Vol. 34, Number 10). American Institute of Physics Inc. https://doi.org/10.1063/5.0109376

Pu, G., Li, X., & Yuan, F. (2021). Numerical study on heat transfer efficiency of regenerative thermal oxidizers with three canisters. *Processes*, *9*(9). https://doi.org/10.3390/pr9091621

Renna, P., & Materi, S. (2021). A literature review of energy efficiency and sustainability in manufacturing systems. In *Applied Sciences (Switzerland)* (Vol. 11, Number 16). MDPI AG. https://doi.org/10.3390/app11167366

Saiful, R., Yandri, E., Hilmi, E., Nasrullah, N., Uhanto, U., Fitriani, F., & Firmandha Ibrahim, R. (2024). Optimizing Motorcycle Manufacturing Sustainability through the Integration of Waste Heat Recovery and Metal Scrap Recycling: A Process Engineering Approach. *Leuser Journal of Environmental Studies*, *2*(2). https://doi.org/10.60084/ljes.v2i2.225

Sharun, V., Rajasekaran, M., Kumar, S. S., Tripathi, V., Sharma, R., Puthilibai, G., Sudhakar, M., & Negash, K. (2022). Study on Developments in Protection Coating Techniques for Steel. In *Advances in Materials Science and Engineering* (Vol. 2022). Hindawi Limited. https://doi.org/10.1155/2022/2843043

Singh, S., Berndt, C. C., Singh Raman, R. K., Singh, H., & Ang, A. S. M. (2023). Applications and Developments of Thermal Spray Coatings for the Iron and Steel Industry. In *Materials* (Vol. 16, Number 2). MDPI. https://doi.org/10.3390/ma16020516

Steinbach, J., Jadachowski, L., Steinboeck, A., & Kugi, A. (2022). Modeling and Optimization of an Inductive Oven with Continuous Product Flow. *IFAC-PapersOnLine*, *55*(27), 184–189. https://doi.org/10.1016/j.ifacol.2022.10.509

Wu, L., Yang, D., Fei, L., Huang, Y., Wu, F., Sun, Y., Shi, J., & Xiang, Y. (2017). Dip-Coating Process Engineering and Performance Optimization for Three-State Electrochromic Devices. *Nanoscale Research Letters*, *12*. https://doi.org/10.1186/s11671-017-2163-0

Xu, W., Wan, B., Zhu, T., & Shao, M. (2016). CO2 emissions from China's iron and steel industry. *Journal of Cleaner Production*, *139*, 1504–1511. https://doi.org/10.1016/j.jclepro.2016.08.107