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Optimizing Motorcycle Manufacturing Sustainability through the Integration of Waste Heat Recovery and Metal Scrap Recycling: A Process Engineering Approach

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Abstract

The automotive industry manufacturing has experienced rapid growth 2–3 times by 2050, with motorcycles constituting around 30% of vehicles worldwide, but this increase in production has significantly heightened the demand for raw materials and energy. A major challenge arises in managing material waste and waste heat generated during the manufacturing process. This research aims to develop a framework that optimizes the synergy between material waste recycling and waste heat recovery to enhance the sustainability of the motorcycle industry, reduce waste, and lower energy consumption. The design leverages waste heat from the melting process to preheat raw materials, raising temperatures from around 50 °C to 350 °C before melting, thereby reducing additional energy needs, lowering emissions, and decreasing operational costs. Utilizing waste heat for preheating not only mitigates environmental impact and thermal load but also significantly improves energy efficiency, ultimately resulting in cost savings and optimized resource use. Utilizing waste heat directly for preheating raw materials has effectively lowered energy consumption by as much as 30%. This approach not only improves operational efficiency but also decreases production costs and minimizes environmental impact, offering a more sustainable solution for the manufacturing sector.



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1. Introduction

The automotive industry has experienced rapid development over the past few decades, with motorcycle manufacturing emerging as one of the most dynamic segments. A significant portion of this rising demand has been fulfilled by the personal transportation sector, with motorcycles making up around 30% of vehicles globally [1]. As production increases, the demand for raw materials and energy has risen significantly. This situation poses new challenges for the industry, particularly in

managing material waste and waste heat generated during the manufacturing process.

The growth in the automotive industry, especially motorcycles, has led to increased demand for raw materials such as aluminum, which is used in various engine components. Global demand for aluminum is expected to increase 2-3 times by 2050 [2]. The production and processing of aluminum require substantial energy and can pollute the environment [3], especially in the melting and casting processes.

Motorcycle manufacturing generates a significant amount of material waste, particularly in the form of metal scraps. Additionally, the manufacturing process also produces a considerable amount of waste heat, primarily during the melting process. According to the IEA, industrial waste heat is the heat contained in all streams leaving industrial processes at a certain time [4]. This waste heat is often not optimally utilized and is simply released into the environment [5], which not only wastes potential energy but can also contribute to global warming.

The environmental impact of motorcycle manufacturing is becoming increasingly concerning due to inefficiencies and pollution from waste heat and metal scraps [6, 7]. Unused waste heat contributes to global warming, while discarded metal, particularly aluminum, depletes natural resources. Moreover, aluminum production is energy-intensive and releases greenhouse gases like CO₂, exacerbating climate change [8, 9]. To address these challenges, the industry must adopt more sustainable practices, including recycling and energy recovery, to reduce its environmental footprint and operational costs.

The integration of a Waste Heat Recovery System (WHRS) in metal casting can significantly reduce energy consumption through innovative preheating techniques. Additionally, effective management of metal scraps through a well-organized logistics system is crucial. Linear programming models can optimize the recycling process, minimizing transportation and processing costs associated with industrial waste [10]. Furthermore, a sustainable circular economy can be achieved by analyzing and optimizing production processes with a focus on economic, environmental, and social sustainability [11, 12]. These strategies not only conserve resources but also reduce environmental impact.

Academic literature has extensively explored various aspects of waste management and heat recovery in the manufacturing industry. A comprehensive review of the aluminum recycling process highlights innovations, new trends, and challenges related to increasing impurities in recycled aluminum alloys [13]. New energy modeling procedures have been developed and applied to enhance efficiency in the thermal processes of the aluminum industry, with the implementation of a WHRS reducing natural gas consumption by over 50% and achieving a payback period of roughly three years [14]. Technological solutions for heat recovery from high-temperature exhaust gases in steel plants, using a dual-media thermal energy storage system with steel slag as a filling material, have demonstrated energy recovery efficiency between 65% and 85% [15]. A method for measuring energy savings in the manufacturing industry utilizing an Energy

Management Control System (EMCS) and the equivalent volume method has also been proposed [16].

Waste heat recovery from aluminum dross and carbon residues through a physical-chemical coupling method has been explained, with enthalpy and exergy analyses indicating an exergy efficiency of 20.4%, despite an exergy loss of 429 MJ [17]. Research on optimization principles in heat recovery system design, involving the use of heat pumps, has shown reductions in energy input by over 70% in case studies [18]. Furthermore, aluminum scrap processing machines have been designed using direct hot air disposal with a conveyor drying system [19]. Research also emphasizes advanced technologies and the environmental impact of aluminum production, with a focus on reducing energy consumption through recycling and waste heat recovery technologies [20]. Finally, a framework has been developed for waste heat recovery in the industrial sector, aiming to reduce both energy costs and environmental impact [21].

Based on the literature review, it is evident that comparative research already exists; however, this study aims to further develop a framework that optimizes the synergy between material waste recycling and waste heat recovery in the context of motorcycle manufacturing. The literature review also highlights that while there has been considerable research and innovation in waste management and heat recovery in the manufacturing industry, there is a specific gap in application for the motorcycle industry. Most research focuses on the aluminum and steel industries, with limited application to other sectors like motorcycle manufacturing.

This research aims to fill that gap by developing a framework to optimize the synergy between material waste recycling and waste heat recovery in motorcycle manufacturing. The focus is on integrating these practices to enhance the sustainability of the motorcycle industry, reduce waste, and lower energy consumption. Related studies demonstrate significant potential for energy savings and environmental impact reduction in other industries, such as heat recovery in aluminum production and the application of thermal energy recovery technologies, which can be applied to improve efficiency in the motorcycle industry.

2. Materials and Methods

2.1. Process Flow Analysis

A comprehensive overview of the stages involved in manufacturing a motorcycle unit can be seen in Figure 1, from the processing of aluminum ingots to the formation of the engine unit. Meanwhile, for the motorcycle body, there are two main components: first, the frame, which

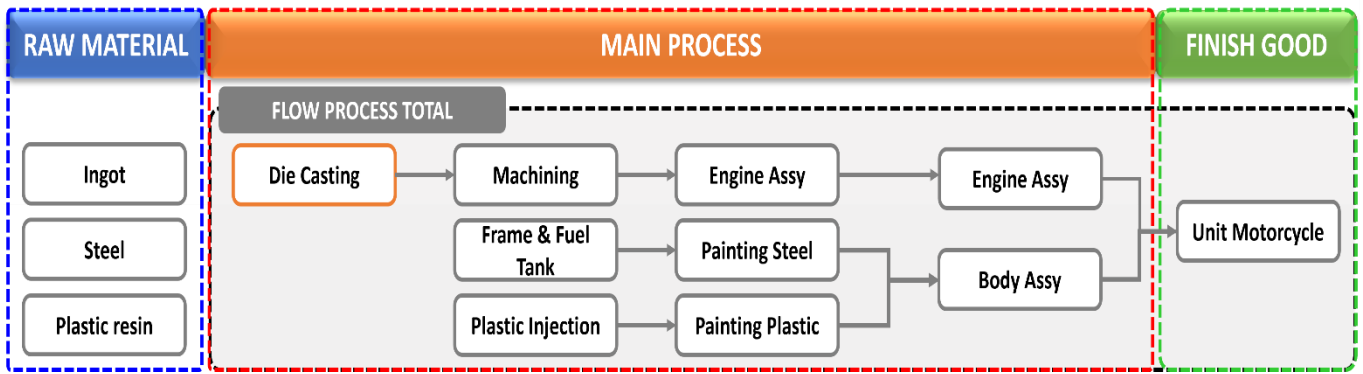


Figure 1. Total flow process unit motorcycle.

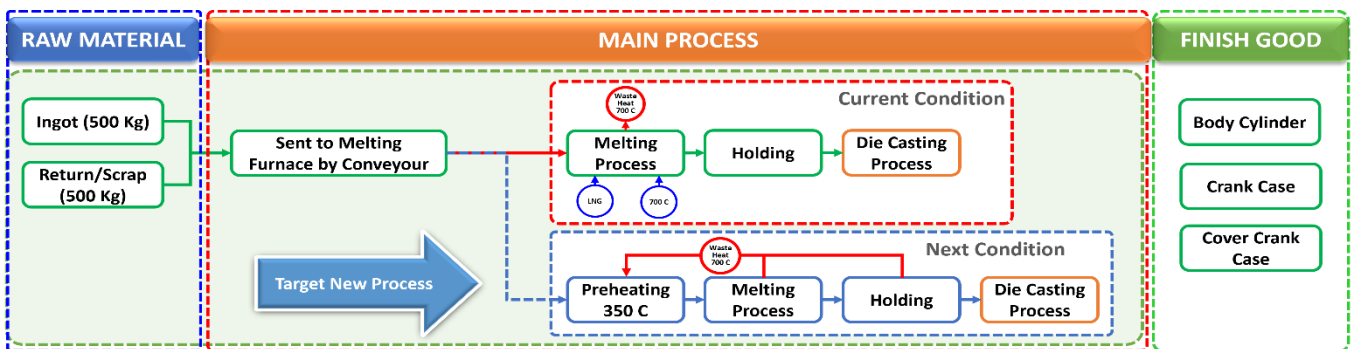


Figure 2. Flow process of die casting.

begins with steel pipes that are formed into the structural frame of the motorcycle, and second, the plastic components, which are made of plastic resin that is molded into the body cover. This process illustrates how each part of the engine and body is produced through various stages of manufacturing.

Meanwhile, for the vehicle body parts, the production flow begins with the welding process, where metal components are joined together through welding. After the welding stage, the parts are then processed in the steel painting department, where the painting is carried out to provide protection and aesthetics to the vehicle body. Following the painting process, they proceed to the body assembly (body assy) to be assembled into a complete body ready to be installed on the vehicle.

The process for plastic parts starts with injection molding, where plastic materials are melted and shaped according to molds with mold temperatures ranging between 70–100 °C [22]. After that, the plastic parts are sent to the plastic painting department to receive a layer of color or protection. These plastic parts are then sent to the body assembly to be assembled with other parts.

The process flow of the die-casting area that will be analyzed in this study to understand the production process and identify opportunities for improving energy efficiency through the utilization of waste heat recovery [23, 24] is illustrated in Figure 2, especially in the melting

process here data is collected for analysis. It is important to comprehensively understand the flow from the input, process, and output stages. The analysis will also include supporting areas such as utilities, maintenance, and engineering. The primary energy source is electricity supplied by the company, while some processes require energy from liquefied natural gas (LNG). In this study, WHR is used directly from one process to another, not for power generation like the Organic Rankine Cycle (ORC) [25].

The overall production process flow for engine parts begins in the die-casting department, where raw aluminum materials are processed into the desired shapes. After the Die Casting process is completed, the parts are then sent to the Machining Department [26]. Next, the parts that have undergone Machining are transferred to the engine assembly area, where these components are assembled into a complete engine. The raw materials can be aluminum ingots or scrap/return.

The first stage of the process begins with approximately 500 kg of aluminum ingots being fed into the system. The use of scrap/return materials helps recycle resources, reducing waste and lowering production costs while also contributing to a reduction in environmental impact [26]. The second stage is the melting process, which consumes 34,200 m³ of gas and 3,334 kW of electricity per month. This process occurs at temperatures between 600–750 °C

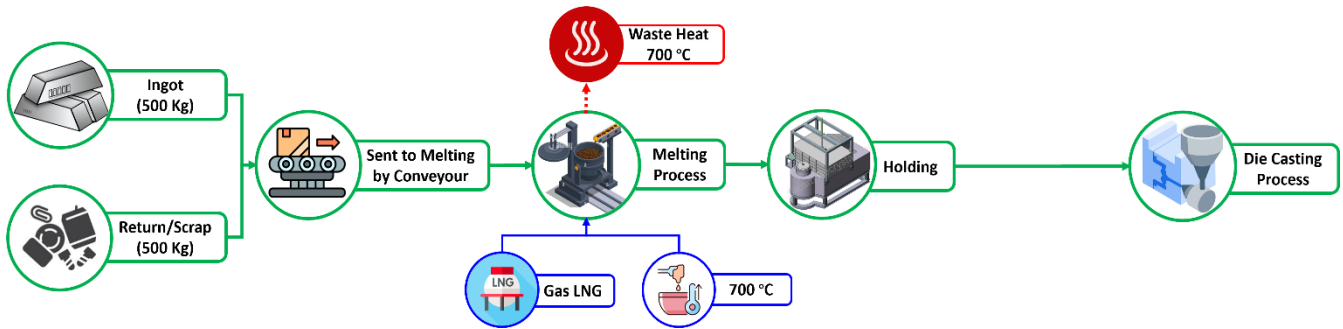


Figure 3. Identification of loss of heat.

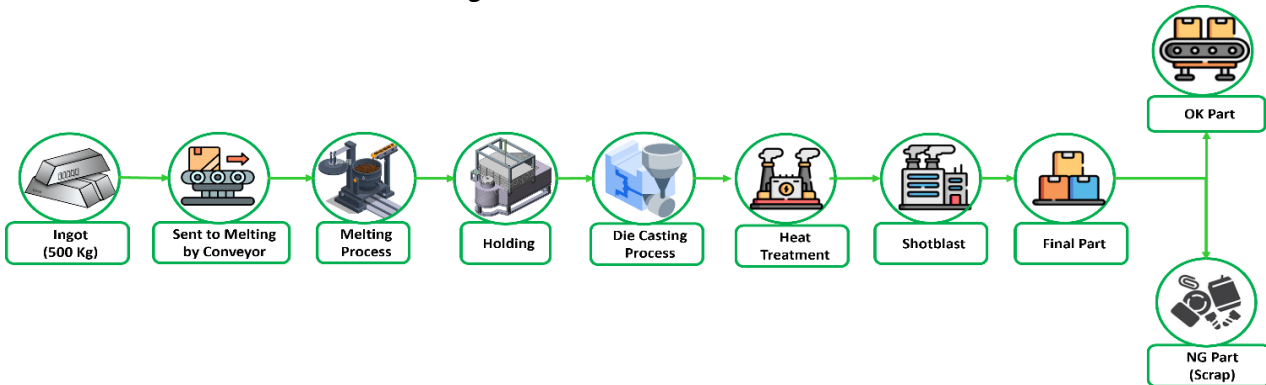


Figure 4. Return or scrap identification source.

to melt the aluminum ingots or scrap. These high temperatures also generate waste heat, which will be recovered and reused through a heat recovery system to preheat the materials before melting. This approach enhances energy efficiency, reduces operational costs, and lowers the environmental impact. The focus of this study on waste heat recovery will be centered on this stage, as illustrated in Figure 3.

The third stage is die-casting, where molten aluminum is injected into a mold under high pressure of around 800 tons [27]. This pressure is applied for approximately 1.3 minutes to shape the aluminum into the final product. The process consumes about 13,500 kW of electricity to operate the machines and maintain the necessary temperature and pressure. Once the die-casting is complete, the next stage begins. The fourth stage is deburring, which aims to remove excess material or burrs left after casting. Deburring can be done automatically using a TC machine to scrape the surface or manually with a file to smooth the edges and refine smaller details more precisely. After deburring, the cylinder body part undergoes heat treatment, while the crankcase part does not require this step.

Heat treatment involves heating the product to approximately 200 °C for several hours to accelerate precipitation and enhance its strengthening effects. This process improves the material's stability and resistance to extreme loads and temperatures without deformation. The fifth and final stage in the production process is shot

blasting, which cleans the surface of materials like iron and steel. This process uses abrasive materials, such as steel shots, that are blasted at high speeds onto the surface. After completing all the production stages, including melting, die casting, deburring, and heat treatment, the parts are placed at the stock point for temporary storage before being transferred to the next department, which is Machining.

In the production process, every product must undergo a quality control check to ensure it meets the established standards. If a part or component is deemed to meet the required standards (OK), it can be immediately sent to the stock point for further shipment preparation or used in the next stage of production. However, if the part does not meet the specified quality standards, it will be classified as NG (No Good) and sent to the scrap area for recycling or disposal, by the production waste handling procedures, as shown in Figure 4.

2.2. Energy and Waste Material Analysis

A detailed overview of the energy sources used at each stage of the production process is provided in Table 1. For instance, in the melting process, two primary energy sources are required: LNG and electricity [28]. The melting process is one of the largest consumers of gas, with consumption reaching 34,000 m³ per month, reflecting the high energy demand to achieve the necessary temperatures for melting aluminum or other materials. On the other hand, the highest electricity

Table 1. Processing energy consumption.

Process	Melting	Die Casting	Deburring	Heat Treatment	Short Blast
Energy source	LNG/Electric	Electric	Electric	Electric	Electric
Energy Consumption	LNG 34.000 M ³ /Month Electric 3.340 kWh/month	13.500 (kW/Month)	7.000 (kW/Month)	12.000 (kW/Month)	3.000 (kW/Month)
Process Temperature	Melting 600 - 750 ^o C Holding 600 - 750 ^o C	600 - 750 (^o C)	50 - 100 (^o C)	700 - 1000 (^o C)	50 - 100 (^o C)

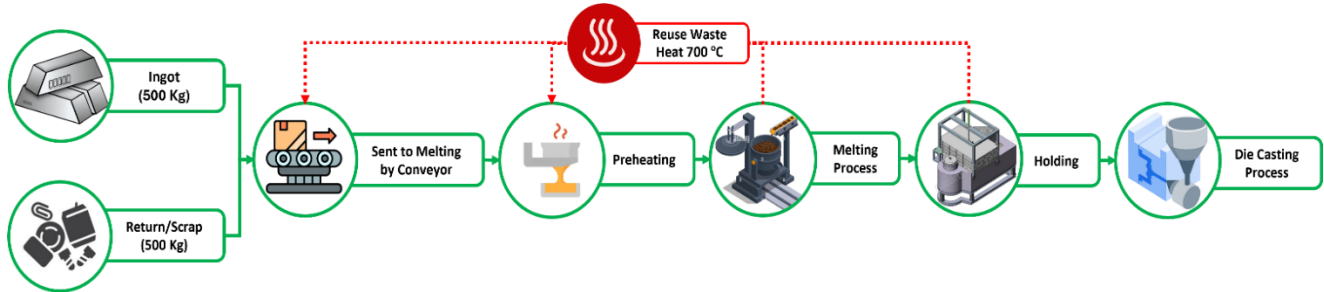


Figure 5. Flow Utilizing waste heat for pre-heating.

Table 2. Energy Consumption

Period	Energy (kWh)			Raw Material (Kg)			kWh/Pcs
	Electric	LNG	Total	Ingot	Return/Scrap	Total Prod	
2023							
Jan	3.348	55.556	58.904	218.140	228.308	120.000	0.491
Feb	3.348	50.987	54.335	199.788	209.946	110.000	0.494
March	3.348	52.366	55.714	205.000	215.809	105.000	0.531
Apr	3.348	32.366	36.188	128.920	134.982	75.000	0.483
May	3.348	51.840	54.893	202.492	211.722	112.000	0.490
June	3.348	52.545	55.578	206.011	213.712	110.000	0.505
July	3.348	35.584	38.932	138.932	147.023	100.000	0.389
Augt	3.348	53.585	56.933	211.185	219.425	115.000	0.495
Sept	3.348	47.491	50.839	187.073	194.563	95.000	0.535
Oct	3.348	54.580	57.928	214.448	224.158	112.000	0.517
Nov	3.348	39.296	42.644	153.251	162.535	115.048	0.371
Dec	3.348	18.063	21.411	72.956	72.956	80.000	0.268

consumption occurs during the die-casting process, where electricity usage reaches 13,500 kW. This table helps identify critical points in the production process where energy consumption is highest, allowing companies to evaluate potential energy savings and operational efficiency.

As shown in Table 1, various energy sources and their consumption are highlighted, and for detailed process insights, refer to Figure 2. Currently, raw materials are sent to the melting process and held (Holding) before being poured into the die-casting stage, where high temperatures of around 750 °C are used to melt the material [29]. However, not all of the heat generated in this process is fully utilized for melting. A significant portion of the heat energy is lost and wasted in the air [30]. Better heat management or the reuse of waste heat could be a key step in improving energy efficiency and reducing operational costs [31].

As shown in Table 2, we identify the percentage of scrap usage compared to pure ingot material for the periods of

2023 and 2024. This comparison is crucial for evaluating the contribution of scrap in the production process, particularly in efforts to reduce the consumption of new raw materials and enhance resource efficiency. By comparing the data from these two periods, we can observe trends in the increase or decrease of scrap utilization and its impact on both material consumption and production cost efficiency. A more detailed analysis of this data is essential for developing strategic steps to maximize scrap usage and minimize reliance on pure ingot materials, contributing to a more sustainable production process.

Moreover, analyzing the potential for energy recovery from waste heat and its impact on overall energy efficiency reveals highly significant results. Waste heat recovery enables the capture and repurposing of energy that would otherwise be lost during production, thereby reducing the need for additional energy input. This not only improves energy efficiency but also lowers operational costs and reduces carbon emissions. These benefits are particularly important in the industrial

sector, where efficient energy use is a critical factor for maintaining competitiveness. By comparing this energy utilization against best practices and benchmarks within the manufacturing industry, we can set higher standards for sustainability and operational efficiency, providing a model for global industries to enhance their energy performance.

2.3. Design of Waste Material Recycling Concept Using Waste Heat

As shown in [Figure 5](#), the plan is to use the waste heat for preheating the raw materials before they enter the melting stage. By applying this method, the initial temperature of the raw materials, which previously was around 50 °C, will significantly increase to approximately 350 °C after undergoing the preheating process. This approach will not only improve energy efficiency by reducing the additional energy required to heat the raw materials, but it will also accelerate the overall melting process, thereby enhancing productivity and lowering operational costs [\[30\]](#). To simplify the analysis of the energy required for LNG gas, we will convert it into kWh using the conversion factor 1 MMBtu = 293 kWh [\[32\]](#).

The data presented in [Table 2](#) will serve as a baseline for comparing energy consumption before and after implementing waste heat utilization for preheating. This information will be essential for evaluating energy efficiency, particularly by comparing energy usage (kWh) per unit of production (Pcs) before and after the application of waste heat recovery technology. This comparison will highlight the extent of energy savings and demonstrate the effectiveness of the preheating method in reducing overall energy requirements.

To improve the efficiency of aluminum scrap recycling, modifications to the existing production process can be proposed. One suggestion is the use of induction furnaces as an alternative to replace oil or gas-fired furnaces [\[33\]](#), which have been shown to reduce aluminum loss due to oxidation. Additionally, controlled atmosphere processing can be applied to minimize contact between molten aluminum and air, thereby reducing the formation of oxide layers. The feasibility of the proposed system can be evaluated through computer-based simulations [\[34\]](#), which will assess the potential for improved energy efficiency and reduced metal loss. These simulations can provide data supporting the economic and technical benefits of the proposed modifications, illustrating the extent to which efficiency improvements and cost savings can be achieved, particularly in reducing energy consumption and metal waste [\[35\]](#). If implemented effectively, this

proposal could set a new benchmark for a more cost-effective and sustainable aluminum recycling industry.

2.4. System Integration and Optimization

In [Figure 5](#), the design concept utilizing waste heat for preheating raw materials is explained, aiming to enhance energy efficiency in the production process by reusing heat that would typically be lost to the environment. By preheating, the raw materials' temperature is raised before entering the next stage of production, reducing the need for additional energy.

Before implementing waste heat recovery, the heat generated during the melting and holding phases was released into the environment at temperatures ranging from 600 °C to 700 °C. This significant energy loss could have been harnessed to prevent both energy waste and thermal impact on the surroundings.

In the new melting process, waste heat is captured and stored in a heat storage system [\[36\]](#), then transferred through a 50-meter-long pipe with a diameter of 200 mm to preheat raw materials such as ingot or scrap/return materials. This system increases the initial temperature of the raw materials from around 50 °C to as much as 350 °C, accelerating the melting process and reducing energy consumption. To ensure the system's continuous efficiency, a computer-monitored control mechanism must be developed [\[34, 37\]](#).

3. Results and Discussion

3.1. Results

The potential for waste material and waste heat utilization in the motorcycle manufacturing process is significant, especially during the die-casting process, as highlighted in this study. At various stages, particularly during the melting phase, substantial amounts of heat are generated but typically go unutilized. In this research, the focus was placed on capturing this waste heat to preheat raw materials, such as ingots and scrap, before they are fed into the smelting furnace. Preheating the materials to around 350 °C before the melting stage reduces the overall smelting time, leading to lower energy consumption, especially in terms of gas used for smelting. The results, as shown in [Table 3](#), demonstrate a clear reduction in energy consumption, with a potential energy saving of up to 30%, as indicated by the kWh/Pcs comparison between 2023 and 2024 ([Figure 6](#)). This reduction not only lowers production costs but also minimizes environmental impacts by reducing heat emissions into the atmosphere. Furthermore, the

Table 3. Result from utilizing waste heat.

Period	Energy (kWh)			Raw Material (Kg)			kWh/Pcs
	Electric	LNG	Total	Ingot	Return/Scrap	Total Prod	
2024							
Jan	3.348	16.420	19.768	175.841	184.900	111.000	0.178
Feb	3.348	18.300	21.653	194.900	207.177	110.007	0.197
March	3.348	17.871	21.219	191.733	200.802	100.000	0.212
Apr	3.348	13.112	16.460	141.562	146.343	80.000	0.206
May	3.348	18.589	21.935	199.765	208.498	112.000	0.196
June	3.348	16.789	20.137	181.025	187.742	104.000	0.194

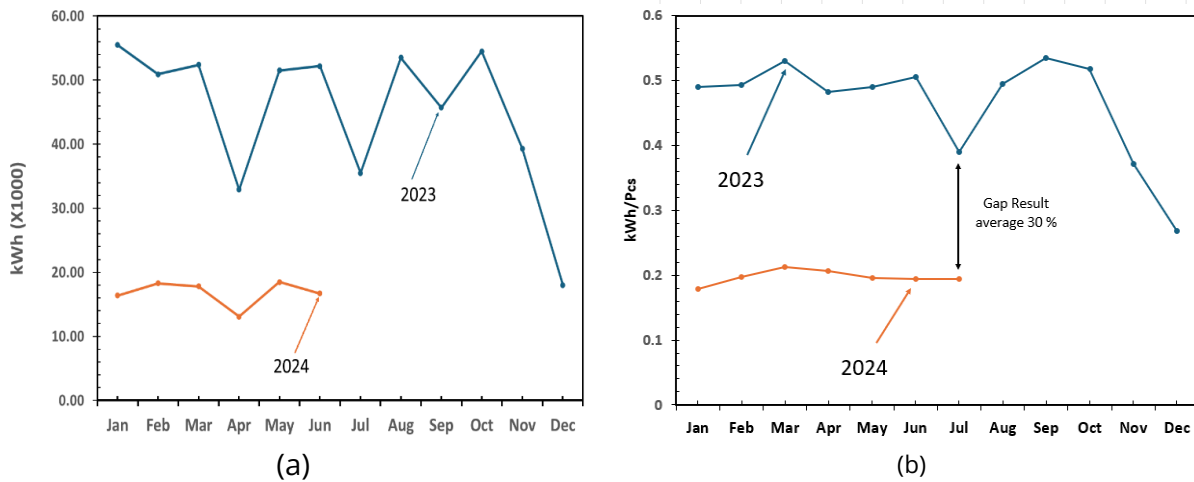


Figure 6. Comparison of (a) energy consumption and (b) results from utilizing waste heat.

recycling process of scrap parts that fail standard checks, as shown in Figure 4, contributes to reducing waste and resource input, making the production process more sustainable.

The integration of waste heat utilization systems and recycling strategies is a crucial step toward sustainable manufacturing in the automotive industry. The research highlights three key areas of focus: improving operational efficiency, advancing technological innovation, and minimizing environmental impacts. The utilization of waste heat directly for preheating raw materials allows for significant energy savings, as shown in Table 3, while simultaneously reducing reliance on external energy sources. This approach aligns with the broader goal of energy optimization, as shown in Figure 5, and supports sustainability through decreased energy demand and lower operational costs. Additionally, the recycling of aluminum scrap within the manufacturing process enhances resource efficiency and significantly reduces the consumption of new raw materials. This closed-loop recycling system minimizes both material waste and carbon emissions, aligning with the industry's environmental goals. The development of integrated monitoring and control systems, is critical for ensuring real-time optimization of these processes, ultimately leading to improved efficiency and sustainability across the motorcycle manufacturing process.

The use of wasted heat in the motorcycle manufacturing process not only provides economic benefits in terms of energy and raw material savings but also contributes to efforts to reduce waste and emissions. The analysis shows that the utilization of wasted heat can be widely applied in industry to improve operational efficiency and achieve environmental sustainability.

Process Flow Concept Diagram as explained in detail as shown in Figure 7, it can be explained that Waste heat generated during the melting process will be optimally utilized for preheating raw materials, including ingots and return or scrap parts. The preheating process aims to increase the initial temperature of the materials to around 350 °C before they are fed into the melting furnace. By increasing the temperature of the raw materials, the time required for the smelting process will be shorter, which directly impacts energy savings, especially the gas used to smelt ingots and scrap. This reduction in smelting time not only improves production efficiency but also lowers operational costs and reduces emissions resulting from excess energy use.

3.2. Discussion

The existing research provides comprehensive insights into the integration of waste heat utilization and recycling strategies in motorcycle manufacturing. This study identifies three main areas for improving system

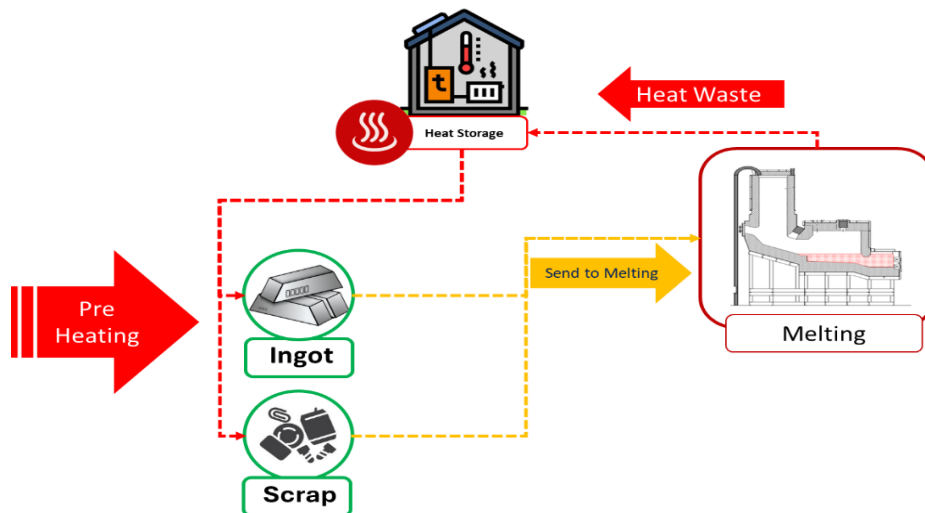


Figure 7. Flow diagram of waste heat utilization concept.

performance and sustainability. These areas focus on operational enhancement, technological innovation to maximize resource efficiency, and minimizing environmental impacts such as CO₂ emissions and waste production [3, 5].

One key focus is the optimization of energy use through the integration of exhaust heat utilization systems [4, 10]. The core of this design lies in the strategic implementation of an exhaust heat utilization system, which captures and reuses energy that would otherwise be lost during the production process. By integrating these systems, energy consumption can be optimized, significantly reducing the need for external energy sources as shown in Table 3. This integration ensures a more sustainable energy supply, lowers operational costs, and improves overall energy efficiency, as described in Figure 5. The development of technologies to utilize waste heat is currently focused more on the conversion of heat into electrical energy. While this is an important step in improving energy efficiency, there are still relatively few technological applications for the direct utilization of waste heat in production processes. Almost all manufacturing processes generate waste heat that can be utilized directly to reduce energy demand [38].

Evaluating the efficiency of aluminum scrap recycling in manufacturing processes plays a crucial role in supporting industry sustainability. This approach not only lowers material costs but also significantly reduces environmental impacts, including the reduction of carbon emissions associated with the procurement of new raw materials. An assessment of the environmental benefits of this integrated system indicates that reducing energy use and carbon emissions can make production processes more ecologically efficient. By directly utilizing waste heat for preheating raw materials, such as ingots

and scrap, previously lost energy can be reused. This not only improves energy efficiency but also reduces reliance on external energy sources. In the future, the development of technologies that enable more efficient, affordable, and easy-to-maintain waste heat utilization will be key. These technologies will allow for improved operational efficiency without requiring large investments in expensive energy conversion technologies [29].

For smaller manufacturers with limited resources, the scalability and affordability of such systems will be pivotal. Low-cost solutions and simplified integration methods will help ensure that even smaller businesses can benefit from increased operational efficiency without the burden of large investments in complex energy conversion technologies [16] which plays a key role in maximizing exhaust heat utilization and recycling aluminum scrap. By enabling real-time monitoring of operational efficiency and energy performance, this system ensures continuous optimization. The integration is expected to significantly improve energy efficiency, reduce raw material consumption, and lower emissions, offering a promising solution for sustainable motorcycle manufacturing. Economically, this system brings considerable cost savings from reduced energy and raw material use, contributing to a faster return on investment. Nevertheless, potential economic risks—such as fluctuations in energy and raw material prices—must be considered when planning implementation. The scalability of this system also makes it adaptable to other manufacturing processes, including the steel, textile, or automotive industries, where high heat output is common. Its broader application will amplify the benefits of energy efficiency and resource reutilization. Future improvements, such as the development of more precise sensor technologies or more responsive automated

controls, will further enhance both efficiency and economic viability.

The implementation of waste heat recovery technologies is often shaped by logistical challenges, especially in supply chain management and existing infrastructure. These challenges can act as obstacles, preventing the successful integration of WHR systems. In terms of supply chain management, the economic feasibility is a significant concern, as high upfront capital expenses and operational costs, along with limited financial support, make it difficult for industries to invest in WHR technologies [39]. A key technical challenge is the inadequate infrastructure for waste heat recovery, which restricts the deployment of this technology. Many industries do not have the essential facilities required to accommodate these systems, limiting their potential for implementation [40].

The exhaust heat utilization system, combined with effective aluminum scrap recycling, can be applied not only to the energy system but also to the wider production process in motorcycle manufacturing. This system makes a significant contribution to improving resource sustainability and reducing carbon emissions for environmental sustainability. This research plays an important role in providing sustainable manufacturing solutions that minimize dependence on non-renewable resources while ensuring the operational efficiency of the production process. For future research directions, the concept of exhaust heat utilization [7] and scrap recycling needs to be further developed considering technological advancements and industry standards. In addition, focus should be given to the optimization of the technical aspects of these systems and their integration with smart manufacturing technologies [26, 41] to improve resource efficiency and operational safety in the motorcycle manufacturing environment.

4. Conclusions

The concept design of sustainability in motorcycle manufacturing through the integration of exhaust heat utilization and scrap aluminum recycling shows that this system is a highly effective solution. The design utilizes the advantages of both technologies to improve energy efficiency and reduce carbon emissions. Exhaust heat utilization maximizes the use of energy generated from the production process, while aluminum scrap recycling reduces dependence on new raw materials, thereby reducing resource consumption and CO₂ emissions. This integration also improves operational sustainability and provides stability of energy supply in the production process. Therefore, the integrated system of exhaust heat utilization and scrap aluminum recycling is a

strategic move that pushes motorcycle manufacturing toward a greener and more efficient direction and addresses today's energy challenges by preparing for a more sustainable future. Moreover, with a focus on decarbonization or reducing carbon emissions, this research emphasizes the important role that recycling and energy recovery technologies can play in minimizing the carbon footprint in the motorcycle manufacturing industry.

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