Design of Development Waste Heat Recovery in Metal Casting Industry: Exploring Energy Saving Potentials

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Abstract*— *The metal casting industry is known for its intensive energy consumption and the significant amount of heat and waste generated during the melting process. If this heat is not utilized, it not only harms the environment but also leads to economic losses. To address this issue, industries are increasingly encouraged to seek sustainable solutions, such as the implementation of Waste Heat Recovery (WHR) systems. The WHR system aims to recover wasted heat and improve energy savings. This solution can also be integrated with hybrid systems that combine fossil fuels with renewable energy sources, such as photovoltaic (PV) panels, batteries, and inverters. Thus, industries can reduce their dependence on fossil fuels and enhance overall energy efficiency. The implementation of WHR technology not only provides technical benefits but also significantly reduces operational costs and carbon emissions. Various simulations have shown that this system can lower production costs per unit. With positive impacts on both economic and environmental aspects, WHR systems offer a more environmentally friendly and sustainable solution for the metal casting industry.

Keywords—Energy Efficiency, Waste Heat Recovery (WHR), Waste Heat and Materials, Energy Consumption Optimization, Carbon Emission Reduction, Industrial Sustainability

I. INTRODUCTION

The metal casting industry is known for its energy-intensive use and the generation of large amounts of waste materials and heat during its processes (Anastasovski et al., 2020). During critical stages such as melting, casting, and cooling, large amounts of waste heat are generated. If this heat is not utilized effectively, it not only causes environmental degradation but also results in significant economic inefficiencies. The need for more sustainable practices has driven the industry to seek ways to optimize energy consumption and reduce material waste. One of the most promising solutions is the implementation of waste heat recovery (WHR) systems. By capturing and reusing waste heat generated during metal casting, industries have the potential to significantly reduce their energy consumption, thereby cutting overall operational costs. The energy savings potential of WHR is substantial, as it allows the reuse of wasted heat energy for additional processes, such as preheating raw materials. This contributes to greater overall efficiency while reducing the industry's environmental footprint (Salonitis et al., 2019). As sustainability becomes increasingly important across various sectors, the integration of WHR into metal casting is crucial.

Academic literature has explored various aspects of waste management and heat recovery in manufacturing industries. Carabalí et al (2018) conducted a study to improve energy efficiency in the metal casting industry sector (ferrous and non-ferrous), which focused on improving energy efficiency to reduce costs, reduce environmental impacts, and increase the competitiveness of the metal casting industry sector through the application of innovative technologies that have been identified. Bonilla-Campos et al (2019) conducted a study in the aluminum die-casting industry by utilizing a model that combines thermal, production, and economic aspects; energy consumption and resource utilization can be evaluated to find the optimal operating configuration. Ortega-Fernández & Rodríguez-Aseguinolaza (2019) conducted a study with the aim of finding an efficient and low-cost technological solution for heat recovery from high-temperature flue gases produced by electric arc furnaces in steel mills. by proposing a double-media dense layer-based thermal energy storage system that uses steel slag as a filler material. Xu et al (2019) conducted research evaluating the potential for energy savings through the utilization of waste heat in the metal casting industry to improve energy efficiency and reduce environmental impact. Egilegor et al (2020) conducted research to recover more than 40% of waste heat in three industrial facilities and reuse the heat in the plant, using efficient and cost-effective heat pipe heat exchangers (HPHEs). Luthin et al (2021) conducted research aimed at identifying the linkages between environmental and economic performance through the integration of LCA/LCC in aluminum production scenarios. The results show that environmental improvements are not always detrimental to the economy, with examples of green electricity reducing global warming potential by up to 70% with little increase in cost. Cao et al (2021)attempted to improve energy efficiency in the complex and energy-intensive die casting process towards greener and more sustainable production. This study proposed a multi-level energy efficiency evaluation framework based on fog-cloud computing to address dynamic production conditions. Su et al (2021) conducted a study by reviewing waste heat recovery technologies in 12 industries, analyzing their thermal performance, economic and environmental benefits, and developing constructive guidelines for researchers and industries, filling the related knowledge gap. Zhang et al (2023)evaluated the environmental impact of aluminum-silicon alloy production from recycled aluminum in China, found that the melting stage had the highest environmental burden, and suggested changes in energy structure and carbon technology to reduce the carbon footprint. Wu et al (2024) developed a network system focused on heat pumps to utilize waste heat in industrial areas with various heat sources and heating loads. A two-stage optimization method was used to match heat sources and heat users.

A literature review indicates that waste heat recovery (WHR) in the metal casting industry has great potential to improve energy efficiency, reduce environmental impacts (Brough & Jouhara, 2020), and reduce operational costs (El Boudali et al., 2022; Huang et al., 2021). Although numerous studies have addressed methods for improving energy efficiency through WHR technology, there is still a lack of comprehensive implementation of WHR in various types of casting industries. Previous studies have not explored the thermal efficiency and energy-saving potential of specific WHR technologies. This study offers a new approach by combining a comprehensive evaluation of WHR from thermal, production, and economic aspects, aiming to find the best configuration for energy efficiency. The main objectives are to model waste heat recovery, evaluate the energy saving potential, and provide solutions to improve sustainability in the metal casting sector (Saiful, Yandri, Hilmi, Nasrullah, et al., 2024).

II. MATERIAL AND METHOD

Concept Design Heat Recovery System Modeling

In this case study, we highlight an aluminum casting plant in Jakarta specializing in the production of motorcycle engine components. The plant is highly productive, with an annual capacity of over one million motorcycles. The technology used is high-pressure die casting (Kan, 2023; Y. Liu & Xiong, 2024), a process in which solid aluminum is melted and then injected into a mold to form the component. This casting process is very energy-intensive, with the main sources being electricity from PLN and LNG gas as fuel (Haraldsson et al., 2021). Among the various production stages, melting solid aluminum into liquid is the most energy-consuming stage (W. Liu et al., 2021). On average, this melting process requires approximately 3,348 kWh of electricity and 154.72 mmbtu of LNG gas, which is equivalent to 45,344 kWh.

Table 1. Implementation overview of WHR Application

Parameter	Implementation		Improvement (%)
	Before WHR	After WHR	
Total Energy Consumption (kWh)	-	-	-
Gas (LNG) Consumption (kWh)	-	-	-
Waste Heat Utilized (kWh)	-	-	-
CO_2 Emission (tons/to of product)	-	-	-

Table 1 will provide a comprehensive overview of the implementation of Waste Heat Recovery (WHR) from various perspectives, namely direct use for heating rather than for ORC (Dokl et al., 2022; Elsaid et al., 2020). In the table, several key aspects that will be discussed include the potential for energy savings, the impact on operational efficiency, and the contribution to reducing carbon emissions (Woolley et al., 2018).In addition, this table also presents data on the cost of implementing WHR technology, the potential for long-term operational cost reductions, and an evaluation of the environmental impact of the implementation of this technology (Papapetrou et al., 2018; Su et al., 2021). By analyzing from technical, economic, and environmental perspectives, this table aims to provide a deeper understanding of the benefits and challenges faced in implementing WHR systems (Douadi et al., 2022; Farhat et al., 2022) in the metal casting industry so that it can be a reference for future strategic decisions. To calculate the waste heat that can be utilized, we need to know the capacity of the WHR system used and how efficient the system is in capturing and converting waste heat into energy. Capacity determines the amount of heat that can be processed, while efficiency indicates how effectively the system utilizes that energy, thereby reducing primary energy consumption and emissions.

We will use Table 2 to compare data between conditions before the implementation of the WHR system in 2023 and after its implementation in 2024. This comparison aims to evaluate the changes that have occurred, both in terms of energy consumption, cost savings, and carbon emission reductions. By utilizing this data, we can analyze the effectiveness of WHR in improving operational efficiency (Yandri et al., 2022) and its impact on the sustainability of the production process. This analysis also provides deeper insight into the potential for reducing operational costs. To simplify the analysis of the amount of energy for LNG gas that we need, we will convert it to kWh using the conversion 1MMBTu = 293 kWh (Thompson & Taylor, n.d.).

Table 2. Energy Usage Comparisson

	Energy (kWh)			Raw Material (Kg)			
Periode	Electric	LNG	Total	Ingot	Return/ Scrap	Total Prod	kWh/ Pcs
2023	-	-	-	-	-	-	-
2024	-	-	-	-	-	-	-

To map the energy flow in production, the first step is to describe each process stage in detail. Figure 1 shows the component manufacturing flow, starting with the delivery of raw materials in the form of aluminum ingots or scrap to the melting process. In the melting stage, energy from LNG gas and electricity is used to melt the aluminum, but some energy is wasted as heat at a temperature of 500-650°C (Oyedepo & Fakeye, 2021; Wazeer et al., 2023). This wasted heat creates energy inefficiencies and environmental impacts. After melting, the molten aluminum is stored in a holding furnace until it is ready for die-casting, a high-pressure injection process into a mold. The resulting part is then sent for finishing or testing before use.

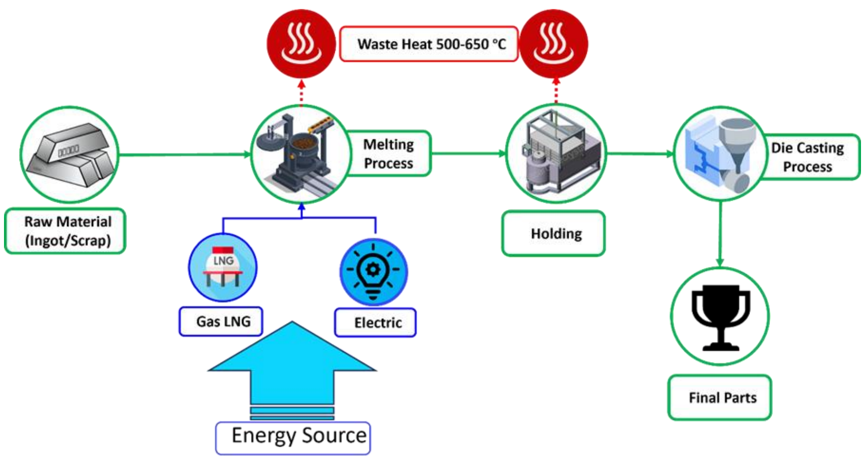


Figure 1. Flow Process Die-Casting

Design Concept of Hybrid

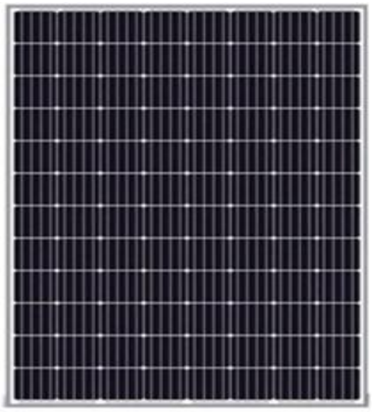


Figure 2. Circuit Concept of PV

We try to create a design concept using renewable energy, in this case energy from solar panels, to be a source of electrical energy in the melting process with a simulation of 30% replacing electrical energy from PLN. To develop a design concept as shown in figure 2, it is necessary to select the main materials and components that will be used in the system. The materials needed include solar panels (PV), batteries, and inverters that function as efficiency, and environmental resistance, while batteries are tailored to their energy storage capabilities. Inverters convert the direct current (DC) generated by the PV into alternating current (AC), which can be directly used by the melting machine and other equipment in the production process.

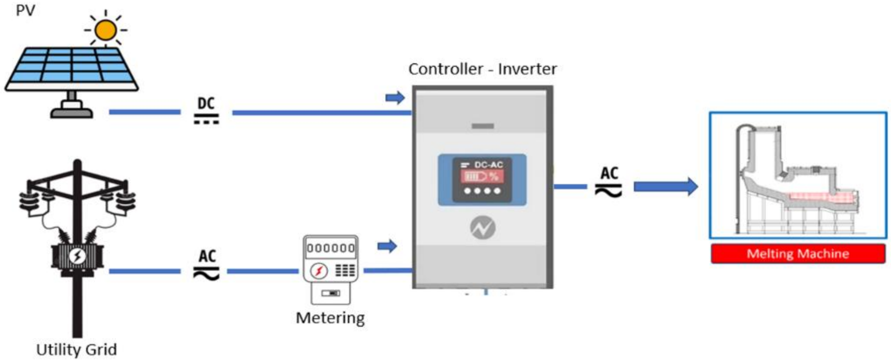


Figure 3. Hybrid Material

a link between the renewable energy system and the electrical load that will be operated. Solar panels will play a role in capturing solar energy and converting it into electricity (Luceño-Sánchez et al., 2019). The inverter will convert direct current (DC) from PV into alternating current (AC) (Sunddararaj et al., 2020; Vairavasundaram et al., 2021) which can be used by the melting machine. Details of the configuration of the PV and inverter can be seen in figure 3.

Table 3 details the specifications of the materials used in the hybrid system. These specifications cover key components such as solar panels (PV) and inverters. Solar panels are selected based on their power capacity, energy conversion

Table 3. Spesification of solar panel

Technical Specification		
1	Modul type	Topsun TS-S255
2	Pmax (WP)	255 W
3	Vmp (Voltage at max power)	31.8 V
4	Imp (Current at maxi power)	8.02 A
5	Voc (Open circuit voltage)	38.2 A

6	Isc (Short circuit current)	8.62 A
7	Power tolerance (%)	± 3%
8	Efficiency (%)	15 – 16%
9	Weight (Kg)	18 Kg
10	Dimention L x W x H (mm)	1640 X 992 X 40 mm
11	Quantity PV	48 Units
12	Inverter 250 kW	2 Units

By using Pvsyst and Heliscope software, we try to analyze the potential use of solar power generation at the location (Latitude -6.19°S, Longitude 106.93°E, Altitude 8 m, Time zone UTC +7). Where we will analyze the performance ratio (PR). Performance Ratio (PR) is the ratio between the final energy produced by the PV system (Final Yield) and the reference energy available based on solar radiation (Reference Yield). We will also look for the solar fraction (SF). Solar fraction is the ratio between the energy supplied by the PV system to the total energy needs, usually expressed as a percentage.

In this new system scheme, the main focus is on utilizing waste heat from the melting process, although waste heat also occurs in the holding stage. The heat generated during the melting process, which was previously left to be wasted without utilization (Jouhara et al., 2018), is now optimized to increase production efficiency. This heat is used to heat the raw material before it enters the melting stage. As explained in Figure 2, the waste heat from the melting process is captured and stored in a heat storage system (Jarimi et al., 2019), which functions as an energy reservoir. The stored heat is then transferred to the raw material for preheating, thereby increasing the initial temperature of the raw material before it enters the melting stage. With this approach, energy consumption in the heating process can be significantly reduced, thereby reducing the need for additional energy in the melting stage.

Energy from solar panels (PV) is optimally utilized during the day when sunlight is available, while at night, electricity demand is diverted to the State Electricity Company (PLN). This system ensures maximum use of renewable energy during the day and a continuous supply from PLN at night.

III. CALCULATION METHOD

First, to ensure the stability and availability of heat energy, an analysis of the utilization of exhaust air from other processes is necessary. Furthermore, consideration should be given to the storage of heat energy from exhaust air into other heat sources, for example, using hot water storage. The stored heat energy can be used as a reserve or for other processes. This method requires further technical and economic analysis.

Second, we calculate the potential energy of the hot air from the oven that can be used for other processes. Waste heat is utilized (Yandri et al., 2022):

$$Q = m\ c_p\ \Delta T$$

Where ṁ [kg/s] is the mass flow rate of air, cp [J/kg^{0}C] represents the specific heat of air, and ΔT is the temperature difference between the initial temperature of the material T_0 [°C] and the temperature of the material after heating T_1 [°C]. A thermocouple is placed in the air duct to measure the temperature of the hot air leaving the oven. We also calculated the resulting emissions as part of the analysis to assess the environmental impact of the implementation of WHR technology. This calculation is important to understand the extent to which the use of the WHR system can contribute to reducing carbon and greenhouse gas emissions. By comparing emissions before and after WHR implementation, we can evaluate its effectiveness in reducing the carbon footprint and its positive impact on the sustainability of the overall production process.

CO_2 Emission (tons/to of product)

$$\text{Emission (ton)} = \text{Energy Consumed (kWh)} \times \text{Emission Factor (kg CO2/kWh)} \qquad (2)$$

Third, we designed an exhaust air system for the preheating process of aluminum raw materials. Several key considerations were considered, such as optimizing exhaust air usage to reduce heat input. We also simulated the use of renewable energy from solar panels. Fourth, we analyzed energy savings and techno-economic value-added. This analysis took into account costs and benefits, including energy savings.

Economic Impact Assessment

In addition to reviewing the technical aspects, we also conducted a techno-economic evaluation to assess how this new design concept provides a significant economic impact. This analysis includes calculating operational cost savings resulting from increased energy efficiency through waste heat utilization. We assessed the potential reduction in energy consumption and its impact on fuel costs and equipment maintenance. In addition, this study also includes a projection of the payback period (ROI) of implementing this new technology, taking into account the initial cost of system implementation, carbon emission reductions, and potential economic incentives related to energy efficiency and sustainability by using the following equation to calculate Return of Investment (Saiful, Yandri, Hilmi, Hamja, et al., 2024; Yandri et al., 2024), where Csave is the energy savings and Cinv is the investment value.

$$ROI = \left[\frac{C_{save}}{C_{Inv}}\right] x\ 100 \quad (3)$$

Energy cost savings also need to be considered because this is an important economic indicator to see the effects of the activities we have carried out.

Energy cost savings (USD/Years)

E Cost Savings (USD) = (E Before WHR − E After WHR) ×E Price (USD/kWh) (4)

Cost Energy

To facilitate the assessment of the effectiveness of Waste Heat Recovery (WHR) implementation, it is important for us to compare the energy costs per unit of product (energy cost/piece) before and after the implementation of the WHR system. This comparison will provide a clear picture of the extent of energy savings achieved and their direct impact on operational efficiency. By evaluating the difference in energy costs, we can more easily measure the economic benefits obtained from WHR technology and determine whether this system is successful in optimizing energy consumption in the production process with the following formula:

$$Cost\ Energy = \frac{Biaya\ Energy}{Jumlah\ part\ yang\ di\ hasilkan} \quad (5)$$
(USD/Pcs)

IV. RESULT AND DISCUSSION

Energy Saving with New System Combination WHR and Renewable Energy

In this new system, energy savings come not only from utilizing waste heat for preheating raw materials but also from optimizing energy use in the initial stages of the melting machine operation. Previously, the melting machine relied on a combination of LNG gas and electricity from PLN. However, in the proposed system, further energy savings are achieved through the adoption of a hybrid system. This system combines electricity from PLN, which comes from fossil fuel sources, with renewable energy generated by solar panels, as seen in Figure 4. By integrating solar panels, this system not only reduces dependence on fossil fuels but also improves overall energy efficiency. The use of renewable energy contributes to reduced operational costs and carbon emissions, thus creating a more environmentally friendly and sustainable solution for production processes in metal casting plants.

Table 4 will serve as baseline data to compare energy consumption results before and after the implementation of waste heat utilization as preheating. This data will be very helpful in evaluating energy efficiency, with a focus on comparing energy consumption (kWh) per unit of production (Pcs) before and after the implementation of waste heat utilization technology.

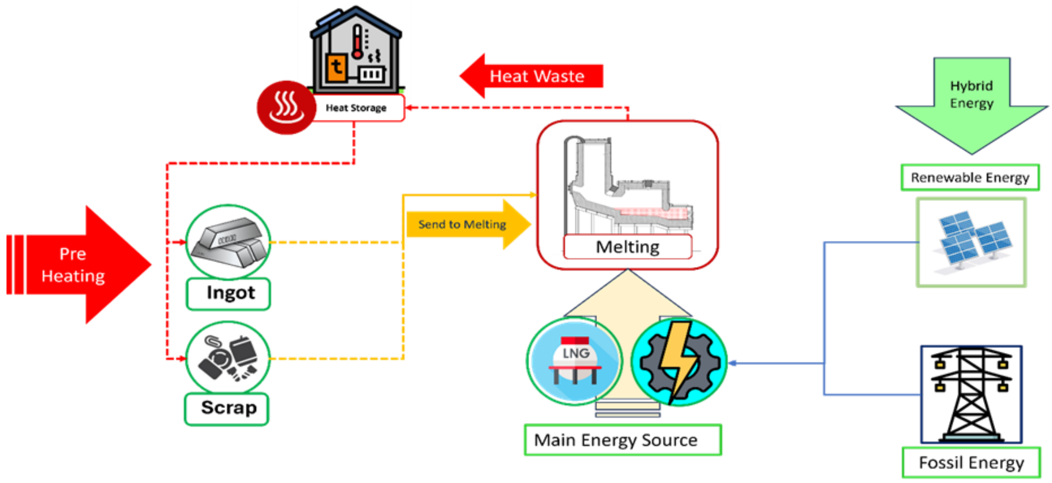


Figure 4. New Hybid System For WHR Utilization

Table 4. Energy consumption data before WHR implementation

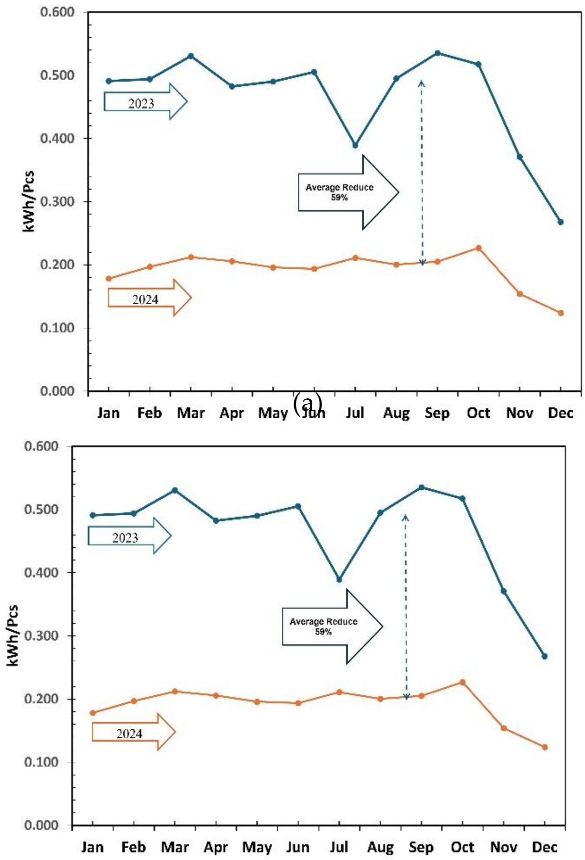
Periode	Energy (kWh)			Raw Material (Kg)			kWh/Pcs
2023	**Electric**	**LNG**	**Total**	**Ingot**	**Return/Scrap**	**Total Prod**	
Jan	3.348	55.556	58.904	218.140	228.308	12.000	0.491
Feb	3.348	50.987	54.335	199.788	209.946	110.000	0.494
March	3.348	52.366	55.714	205.000	215.809	105.000	0.531
Apr	3.348	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
Des	3.348	18.063	21.411	72.956	72.956	80.000	0.268

The utilization of waste heat through the Waste Heat Recovery (WHR) system has successfully demonstrated a significant reduction in energy consumption, measured in kWh/Pcs. This is clearly visible in Table 5, where a comparison of energy consumption before and after WHR implementation reveals substantial savings. This reduction in energy consumption not only reflects higher energy efficiency but also contributes to reduced operational costs and a lower environmental impact, making this technology highly effective in improving the sustainability of production processes.

Table 5. Energy Consumption Data After WHR Implementation

Periode	Energy (kWh)			Raw Material (Kg)			kWh/Pcs
2024	Electric	LNG	Total	Ingot	Return/Scrap	Total Prod	
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
July	3,348	18,799	22,147	201,759	211,165	105,000	0.211
Augt	3,348	18,098	21,447	194,272	203,259	107,000	0.200
Sept	3,348	17,171	20,521	185,012	192,162	100,000	0.205
Oct	3,348	17,073	20,423	195,000	192,000	90,000	0.227

Our simulation results provide a clear picture of the significant energy savings achieved through the implementation of Waste Heat Recovery (WHR) technology. To facilitate understanding, these savings are presented visually in Figure 5, which compares energy consumption before and after WHR implementation. This graph demonstrates a significant reduction in energy use, thus strengthening the validity of WHR implementation as an efficient solution for optimizing energy use in the metal casting industry.



(a)

Figure 5. Comparrison Of (a) Energy Consumption And (b) Result Utilizing

The simulation results of the Waste Heat Recovery (WHR) system applied to the metal smelting industry show very favorable results, as can be seen in Table 6. The data from the table indicates significant energy savings after the implementation of WHR technology. This reduction in energy consumption not only helps in lowering operational costs but also has a positive impact on the environment by reducing carbon emissions. The effectiveness of the WHR system in utilizing waste heat has been proven to increase the efficiency of the metal smelting process, making this technology a very promising solution for a more sustainable and energy-efficient industry.

Table 6. Result Simulation Of WHR

Parameter	Implementation WHR		Improvement (%)
	Before	After	
Energy Consumption avg (kWh)	45,930	16,800 (b)	64
Gas (LNG) Consumption avg (kWh)	45,344	17,222	62
Potential WRH Utilized (kWh/Pcs)	0.464	0.192	59
CO_2 Emission (tons/to of product)	544,123	16,099	97

Identification of Energy Usage

Table 7 below explains the parts of the melting machine that use electrical energy and gas energy.

Table 7.
Energy usage on melting

Tahapan Proses	Energi yang Digunakan	Komponen Terlibat	Fungsi / Keterangan
1. Pemanasan Crucible	Gas	Burner gas, ruang bakar utama	Mencapai suhu leleh logam aluminium
2. Preheating Material	Gas + Panas Buang	Jalur preheating berbasis WHR	Memanaskan scrap sebelum masuk ke crucible
3. Peleburan Logam	Gas	Chamber utama, burner, termokopel	Proses peleburan terjadi dengan nyala api langsung
4. Pengadukan (Agitasi)	Listrik	Motor agitator, gear penggerak	Menjaga homogenitas dan distribusi suhu logam cair
5. Sistem Kendali	Listrik	PLC, sensor suhu, sensor level	Kontrol otomatis suhu, volume, dan proses leleh
6. Safety & Ignition	Listrik	Ignitor listrik, alarm suhu, katup otomatis	Menyalakan burner, shutdown otomatis jika terjadi abnormal
7. Pengisian & Pelepasan	Listrik	Conveyor, pintu hidrolik, pompa hidrolik	Mengatur masukan dan pelepasan logam cair
8. Sistem Pendingin	Listrik	Kipas atau sirkulasi air/water pump	Mendinginkan komponen elektronik dan motor

Meanwhile, Table 8 shows the energy consumption after implementing a hybrid system combining existing fossil fuel sources with renewable energy from solar panels. In this simulation, we only utilized this renewable energy source, representing 30% of the total electrical energy requirements of the melting machine.

Table 8.
Comparisson Of Energy Usage

Month	Energi (kWh)					Raw Material (Kg)			kWh/Pcs	
	Fossil	PV	LNG		Total (kWh)	Ingot	Return	Total Prod (Pcs)	Fossil	PV
Jan	2,344	1,004	56.03 MMBTU	16,420 kWh	18,763	175,841	184,816	94,733	0.209	0.198
Feb	2,344	1,004	62.46	18,305	20,648	194,895	207,167	104,087	0.208	0.198
March	2,344	1,004	60.98	17,871	20,214	191,733	200,802	96,745	0.219	0.209
Apr	2,344	1,004	44.74	13,112	15,455	141,562	146,434	74,851	0.220	0.206
May	2,344	1,004	63.42	18,587	20,930	199,765	208,498	106,822	0.205	0.196
June	2,344	1,004	57.29	16,789	19,132	181,025	187,742	88,115	0.229	0.217
July	2,344	1,004	64.15	18,799	21,143	210,759	211,165	104,889	0.211	0.202
Augt	2,344	1,004	61.75	18,098	20,443	194,272	203,259	105,841	0.203	0.193
Sept	2,344	1,004	58.59	17,171	19,516	185,012	192,162	98,144	0.209	0.199
Oct	2,344	1,004	58.25	17,073	19,418	195,000	192,000	99,000	0.206	0.196

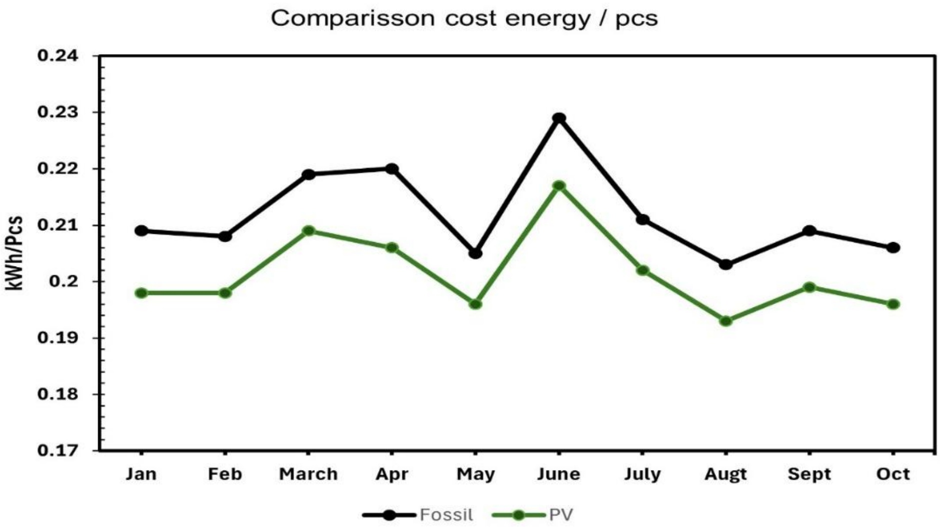


Figure 6. Cost Energy

Based on the simulation results, if 30% of the electricity needs that were previously supplied entirely from fossil energy sources are replaced through a hybrid system using solar panels, then the energy cost per unit of product (cost energy/pcs) will decrease by an average of 11% in a one-year period, as shown in figure 6. These annual savings not only reduce operational costs significantly but also reduce dependence on fossil energy, reduce carbon emissions, and make a real contribution to the company's sustainability targets. With a solar panel lifespan that can reach 20–25 years, the initial investment has the potential to be returned within 5–7 years through accumulated energy cost savings.

Figure 5a shows a comparison between total energy consumption before and after the implementation of the Waste Heat Recovery (WHR) system. The results show that the implementation of WHR is able to consistently reduce total energy use by an average of 59%. The energy efficiency resulting from this system has a significant impact on overall energy savings. Meanwhile, Figure 5b shows that LNG gas usage also experienced a significant decrease, with an average savings of

64%. This decrease indicates that in addition to reducing electricity consumption, the implementation of WHR is also effective in reducing the use of fossil-based energy sources, such as LNG gas, which ultimately contributes to reduced carbon emissions and lower operational costs.

Performance Ratio and Solar Fraction

Figure 7 shows a graph of normalized energy production (per installed kWp) for each month of the year. The graph is divided into four different energy categories, Lu: Unused energy (battery full)—Energy that is not used because the battery is full, amounting to 1.06 kWh/kWp/day, shown in blue. Lc: Collection Loss (PV-array losses) - Collection losses (PV array losses), amounting to 0.85 kWh/kWp/day, shown in purple. Ls: System losses and battery charging—System losses and battery charging, amounting to 0.27 kWh/kWp/day, shown in green. Yf: Energy supplied to the user—Energy supplied to the user, amounting to 2.63 kWh/kWp/day, shown in red. The graph also shows how the energy produced by the PV (photovoltaic) system is divided into different categories of use and loss throughout the year. This is relevant to understanding the efficiency and energy distribution of PV systems, as well as to identifying potential areas for efficiency improvement.

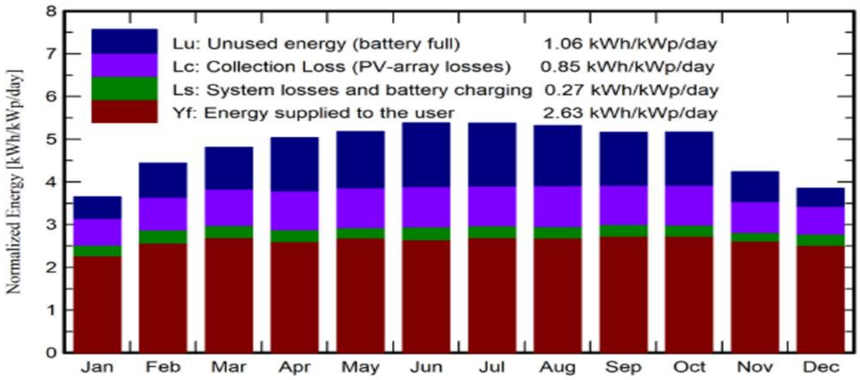


Figure 7. Normalized Energy Production

Figure 7 shows the Performance Ratio (PR) fluctuating depending on the time of day, but overall, it shows good performance. Meanwhile, the Solar Fraction (SF) in May, July, September, and October was at 100%, meaning that PV was able to meet the load's energy needs during those months. Annually, the solar fraction was at an excellent 96%, meaning that PV was able to meet most of the energy needs.

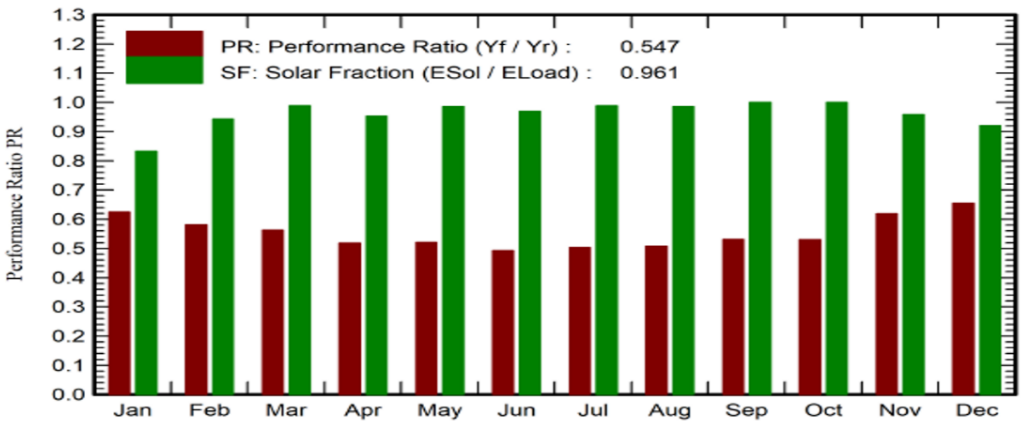


Figure 8. Performance Ratio

Figure 8 shows the various sources of losses in the system, with temperature being the primary factor, contributing 6.1% of the losses. The next factor is component mismatch, contributing 3.9%, followed by light reflection at 3.3% and dirt or dust at 2%. Meanwhile, shading only contributes 0.4% of the losses, indicating a relatively small impact compared to the other factors. This diagram provides important insights into the largest sources of energy loss in the system that can be focused on for efficiency improvements.

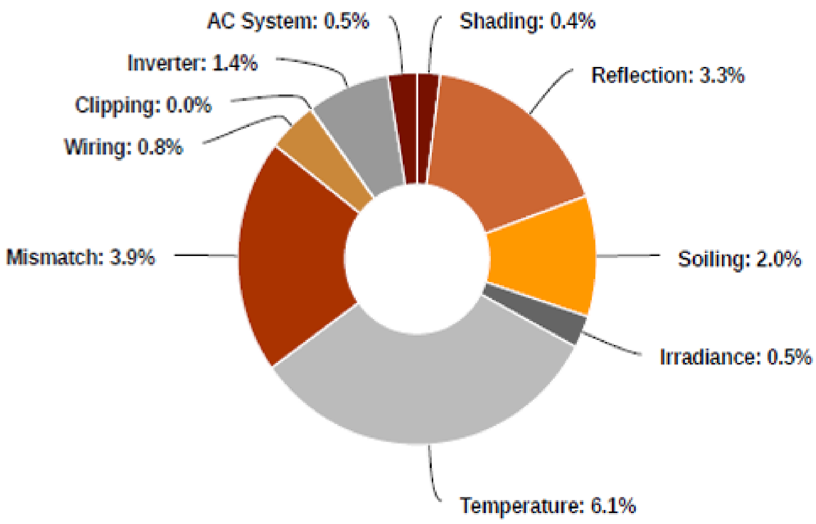


Figure 9. Loss System Data

Cost Efficiency

Table 6 displays various important indicators related to the effectiveness of the Waste Heat Recovery (WHR) system implementation. Some of the indicators that can be identified include a decrease in overall energy consumption, as well as a reduction in the use of LNG (Liquid Natural Gas) as the primary energy source in the metal smelting process. Furthermore, there was a significant decrease in energy-saving costs achieved; this is due to the drastic reduction in energy consumption after the WHR implementation. This reduction in energy consumption has a direct impact on lowering operational costs, allowing the company to allocate funds for other needs. The resulting efficiency not only reduces production costs but also impacts the price of the final product, making it more competitive in the market. Overall, the WHR implementation has successfully increased the company's profitability by reducing reliance on fossil fuels and significantly lowering operational costs.

Table 9. Efficiency of Electric

Efficiency of Electric			
Item	Electric Consumption / month		Efficiency
	Before	After	
kWh	3,348.00	2,343.83	29.99%
Cost (USD)	238.21	166,78	29.99%

Based on the analysis results in Table 9, the implementation of the hybrid system successfully increased the efficiency of monthly electricity consumption by 29.99%, which has a direct impact on reducing energy costs. Before implementation, the average electricity cost reached IDR 75,000,000/month (approximately USD 4,687.50 at an exchange rate of IDR 16,000/USD) with electricity consumption of 50,000 kWh. After implementation, electricity costs decreased to IDR 52,507,500/month (approximately USD 3,281.72) with electricity consumption of 35,005 kWh. This resulted in savings of IDR 22,492,500/month (approximately USD 1,405.78) or a total of IDR 269,910,000/year (approximately USD 16,869.38/year). In addition to the economic benefits, this reduction in electricity consumption is equivalent to a reduction in carbon emissions of ±152.95 tons of CO_2 per year (assuming an emission factor of 0.85 kg CO_2/kWh), which significantly supports sustainability efforts and reduces the industry's carbon footprint.

Environmental Impact

The implementation of the Waste Heat Recovery (WHR) system and the partial replacement of fossil fuels with renewable energy has significantly reduced carbon emissions, as shown in Figure 6. By optimizing waste heat utilization and integrating renewable energy sources such as solar panels, the metal casting industry has been able to reduce the carbon footprint generated from the production process. This emission reduction not only supports global efforts to address climate change but also strengthens the industry's position in meeting increasingly stringent environmental standards. Furthermore, the WHR system makes a significant contribution to the implementation of the circular economy concept, where previously wasted heat energy is reused in the production process. This allows for a reduction in primary energy use while optimizing existing resources. The WHR's contribution supports the improvement of the sustainability of the metal casting industry by creating more efficient and environmentally friendly processes, as well as reducing energy and material waste. Ultimately, the implementation of this system is a strategic step in driving the industry towards more sustainable and competitive operations.

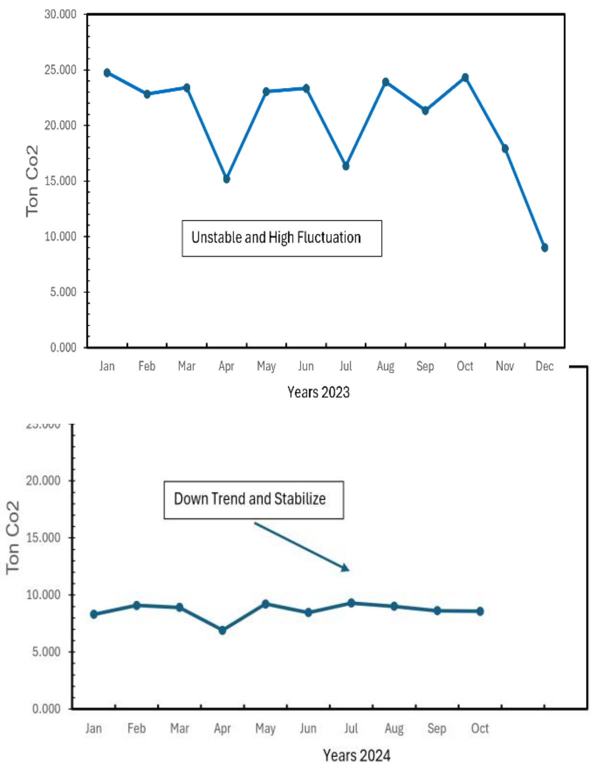


Figure 10. Result Emission

The use of the Waste Heat Recovery (WHR) system has a significant impact on reducing emissions, as shown in Figure 10. Before the implementation of WHR, emissions tended to be higher and fluctuating, in line with energy consumption, especially from LNG, as seen in Figure 10a. This instability indicates the high intensity of emissions when the thermal energy from LNG is not optimally utilized. However, after the implementation of WHR, emissions showed a more consistent and stable decrease, as seen in Figure 10b. The use of WHR successfully reduced and regulated emissions, reflecting the effectiveness of this technology in supporting efforts to reduce the environmental impact of the industry.

DISCUSSION

Existing research provides comprehensive insights into the integration of waste heat recovery and renewable energy as the primary energy source in the process. This study identifies three key areas for improving system performance and sustainability. These areas focus on operational improvements, technological innovations to maximize resource efficiency, and minimizing environmental impacts such as CO_2 emissions and waste production (El Boudali et al., 2022; Jouhara et al., 2018; W. Liu et al., 2021).

First, Table 6 shows a comparison of waste heat utilization before and after the application, demonstrating significant improvements in several key parameters. These improvements include energy recovery efficiency, emission reduction, and overall energy savings. Furthermore, a comparison of the cost per unit (cost/unit) across various simulation scenarios demonstrates a consistent reduction in production costs. This indicates that the implementation of waste heat recovery technology not only provides positive technical impacts but also yields clear economic benefits. This cost reduction demonstrates that waste heat utilization through this new system is highly effective, both in reducing operational costs and in increasing energy efficiency throughout the production process.

Second, from an environmental sustainability perspective, reducing carbon emissions is not the only significant benefit. The use of waste heat recovery (WHR) also directly contributes to the implementation of a circular economy. By utilizing waste heat that would otherwise be lost without utilization, this system enables a more efficient and sustainable energy cycle, where waste energy is recycled to support production processes. This reduces dependence on primary energy and supports the principles of a circular economy that focuses on efficiency and waste reduction. From an economic perspective, implementing this system has various implications. Significant energy savings can result in lower operational costs, while the use of renewable energy sources such as solar panels helps reduce dependence on fossil-based electricity from the state electricity company (PLN). From a return on investment (ROI) perspective, although there are significant initial costs for installing a WHR system and solar panels, in the long term, the energy savings and reduced production costs per unit can yield a promising ROI. However, potential economic risks must also be considered, such as the maintenance costs of new technology, changes in energy prices, and fluctuations in the raw material market for renewable energy technologies.

Third, it is important to consider the scalability of this system to other manufacturing processes or even industries beyond metal casting. WHR technology and the integration of renewable energy have great potential for application in various industrial processes that utilize high heat, such as steel or cement production. The system can also be adapted to plants of different scales, depending on energy requirements and production capacity. The future of this system also opens up opportunities for further innovation. More advanced heat storage technologies or deeper integration with renewable energy could improve the overall efficiency of the system. Further research into new materials for solar panels or energy storage systems could also help reduce costs and improve efficiency, making the proposed WHR system increasingly economical and feasible for wider adoption.

This research contributes important insights into the integration of waste heat recovery and renewable energy to improve efficiency and sustainability in industrial processes. The study significantly demonstrates improvements in energy recovery efficiency, emission reductions, and operational costs through the application of waste heat recovery (WHR) technology and renewable energy systems. The research's significance lies in its contribution to the implementation of a circular economy and energy savings, as well as its potential for generating a favorable return on investment (ROI). Directions for future research include the development of more efficient heat storage technology innovations, deeper integration with renewable energy, and the application of these systems to various manufacturing processes to achieve greater economic and environmental benefits.

V. CONCLUSION

This study found that a hybrid system integrating PLN electricity with renewable energy from solar panels, while utilizing waste heat recovery (WHR), can significantly reduce dependence on fossil fuels, improve energy efficiency, and lower operational costs. Simulations of the combined energy mix show that the use of WHR and renewable energy can reduce carbon emissions and generate significant savings. Furthermore, the implementation of WHR supports the concept of a circular economy by utilizing waste energy for production processes, thereby reducing primary energy use. Despite the high initial costs, the promising potential return on investment (ROI) and the wider industrial scale of this technology offer positive prospects for future energy efficiency and sustainability.

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