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# Circular energy integration: Optimization of refuse derived fuel pellets and residual heat recovery for industrial decarbonization

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## ABSTRACT

**Background:** Indonesia's industrial sector contributes 36% to national carbon emissions with 30-60% of thermal energy wasted as residual heat, while 68.5 million tons of waste per year, 60-70% of which is inorganic waste, is not managed optimally. **Methods:** This study used a literature review method with a systematic approach to examine and analyze the circular energy integration system. The literature sources used included Scopus and Web of Science indexed international journals, accredited national journals, reference books, and policy and regulatory documents related to waste and energy management in Indonesia. **Findings:** This system combines three main components, namely the production of RDF (refuse derived fuel) pellets from inorganic waste, the recovery of residual heat from industrial processes, and a real-time emission monitoring system to ensure environmental compliance. The integration of these three components creates synergies that not only reduce waste volume and greenhouse gas emissions but also produce alternative energy that can substitute fossil fuels in industrial applications. **Conclusion:** This study suggests that system integration can assist in implementing industrial decarbonization. **Novelty/Originality of this article:** The innovative aspect presented is the integration of RDF Pellets as co-firing with the utilization of residual heat in boilers so that it can be fully utilized.

**KEYWORDS**: climate change; industrial decarbonization; RDF pellets; residual heat recovery.

## 1. Introduction

Indonesia currently faces a double challenge in terms of the environment and energy. Overall, the industrial sector contributes 36% of total greenhouse gas emissions worldwide, with nearly 90% of Indonesia's energy sources still using fossil fuels such as coal for primary energy (Astuti et al., 2025). However, this high energy consumption is not matched by energy efficiency, with 65% of thermal energy wasted into the air as residual heat without being reused (Digdoyo et al., 2021). On the other hand, incomplete combustion of fossil fuels will result in the formation of carbon monoxide, which can trigger the formation of harmful tropospheric ozone (Rofida, 2025). Tropospheric ozone contributes directly to the greenhouse gas, so one of the tangible impacts that can be felt is extreme climate change

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(Vongelis et al., 2025). On the other hand, dioxin and furan compounds are predominantly derived from power plants and heating (66%), the pulp and paper industry (21%), uncontrolled burning (7.7%), and the iron and non-iron industries (4.5%) (Efrizal, 2022).

On the other hand, Indonesia produces an average of 68.5 tons of waste per year, with 15-20% of the total 68.5 tons per year being properly managed. Improper waste management can have various negative impacts on the environment, one of which is the phenomenon of microplastic rain. Not many people realize that the recent microplastic rain phenomenon in Jakarta is not only a stark warning of the environmental pollution crisis, but also a warning of the lack of inorganic waste management, especially plastic, in Indonesia (BRIN, 2025). Generally, plastic waste in Indonesia is only managed by burning or burying it. In addition to the above sources, burning waste with an imperfect combustion system results in the formation of toxic compounds in the form of dioxins and furans (Baca et al., 2023).

Microplastics have a negative impact on the environment and human health. One of the negative impacts of microplastics on aquatic organisms is the death of aquatic microorganisms because microplastics are very small and often resemble plankton, which is a food source for marine organisms (Amanu et al., 2024). On the other hand, the accumulation of microplastics in the human body also has negative health impacts, such as heart disease, cancer, and even autoimmune disorders (Emenike et al., 2023). Thus, Indonesia's challenges in the environmental and energy sectors require special attention and immediate action.

One appropriate solution that can be applied to address these two issues is to utilize plastic waste into RDF Pellets in synergy with Residual Heat Recovery technology, in order to reduce the impact of environmental damage while maximizing the utilization of available energy. RDF pellets are a fuel that is compacted and processed through mechanical and thermal processes, with one of the fuels being plastic waste with a calorific value made from non-hazardous solid waste, whose energy can still be reused (Taufiqurohim et al., 2025).

RDF with plastic as its base material has a calorific value ranging from 15 to 25 MJ/kg (Sharma et al., 2025). The selection of low PVC and chlorine plastic as the base material for RDF pellets aims to reduce the production of dioxins and furans generated during the combustion of RDF pellets as an energy source (Mulhidin et al., 2022). Therefore, based on this, the use of RDF pellets as an alternative, renewable, and environmentally friendly energy source has great potential to replace fossil fuels such as coal as an energy source.

Residual heat recovery is a system that uses a thermodynamic cycle similar to that of a conventional coal-fired power plant, with a system that converts mechanical energy into electrical energy or other forms of energy (Prestanty & Cahyono, 2022). The energy source for residual heat recovery or waste heat recovery comes from exhaust gas or flue gas available in the reactor system. Residual heat recovery can be reused by more than 80%, because generally untreated exhaust gas is at a temperature of 480 $^{o}$C to 600 $^{o}$C (Cho et al., 2023). The use of thermodynamic cycles in residual heat recovery generally consists of four types, namely Trilateral Flash (TFC), Transcritical$CO_2$ Cycle (T- 54 CO(2) Cycle, Kalina Cycle (KC), and Organic Rankine Cycle (ORC), each with their own advantages and disadvantages (Oyedepo & Fakeye, 2021). Thermoelectric Generators (TEGs) are one of the important tools in reactors that function as direct electricity conversion devices, which reduce the need to convert heat from mechanical energy into electrical energy and have the ability to reduce the amount of $CO_2$in combustion systems (Farhat et al., 2022).

Amid these issues, students, as agents of change, have a crucial and important role in designing innovative solutions to support industrial decarbonization in Indonesia and encourage the realization of several Sustainable Development Goals, such as SDG 7 (affordable and clean energy), SDG 9 (industry, innovation, and infrastructure), and SDG 13 (climate action). Through the integration of RDF pellets by utilizing low PVC and chlorine plastic waste and the use of Residual Heat Recovery technology accompanied by an emission sensor system with the use of a thermoelectric generator, it is hoped that environmental problems can be reduced.

## 2. Methods

### 2.1 Systematic literature riview

This study employs a systematic literature review method to examine the circular energy integration system by gathering data from international journals indexed in Scopus and Web of Science, accredited national journals, and relevant regulatory documents in Indonesia. The literature selection process is limited to publications ranging from 2012–2025 focusing on waste-to-energy, RDF, and heat recovery technologies to ensure the relevance and novelty of the data, which is analyzed holistically from both technical and economic aspects.

### 2.2 Thematic analysis and regulatory validation

The collected data is analyzed thematically to identify key components such as RDF pellet production, heat recovery systems, and emission control, as well as their contribution to the Sustainable Development Goals (SDGs). Concept validation is performed through cross-referencing procedures with national standards, specifically the Minister of Environment Regulation No. 70 of 2016, to ensure that the analysis of this integrated system remains aligned with the applicable emission quality standards and thermal waste management regulations in Indonesia.

## 3. Results and Discussion

### 3.1 Circular energy integration

Circular energy integration is a new paradigm in waste and energy management that integrates circular economy principles with sustainable energy conversion technology. This system combines three main components, namely the production of RDF pellets from inorganic waste, the recovery of residual heat from industrial processes, and a real-time emission monitoring system to ensure environmental compliance. The integration of these three components creates synergies that not only reduce waste volume and greenhouse gas emissions but also produce alternative energy that can substitute fossil fuels in industrial applications (Sesay & Fang, 2025). This system approach is in line with the concept of industrial symbiosis, where waste from one process becomes input for another process, creating a circular flow of materials and energy (Chertow, 2007).

The concept of circular energy integration adopts a waste management hierarchy that places prevention and reduction at the top, followed by reuse, recycling, energy recovery, and disposal as a last resort. In this context, the production of RDF pellets falls under energy recovery, which maximizes the value of materials that cannot be recycled conventionally. This transformation of waste into alternative fuel not only reduces dependence on landfills but also creates a closed loop in the industrial energy system. Waste heat recovery strengthens the circular dimension by capturing energy that was previously wasted from combustion processes or other industrial operations, then converting it into thermal energy that can be used for production or heating purposes.

Real-time emission monitoring systems are a critical element that distinguishes circular energy integration from conventional waste-to-energy conversion approaches. Advanced sensor technology and Internet of Things (IoT) systems enable continuous, high-precision detection and analysis of emission parameters such as particulates, NOx, SOx, CO, and heavy metals. The data collected is not only used to ensure compliance with emission quality standards set out in environmental regulations, but also for adaptive combustion process optimization. Automatic control systems can adjust operational parameters such as air-fuel ratio, combustion temperature, and residence time in the combustion chamber based on real-time feedback from emission sensors, thereby maximizing energy efficiency while minimizing environmental impact.

In Indonesia, the implementation of circular energy integration systems is becoming increasingly relevant given the government's target to reduce greenhouse gas emissions by 29% through its own efforts or 41% with international support by 2030 in accordance with the updated Nationally Determined Contribution (NDC). The circular energy integration system contributes directly to the achievement of this target through the reduction of methane emissions from waste piles and the substitution of fossil fuels with renewable energy. Furthermore, the implementation of this system supports the achievement of the Sustainable Development Goals (SDGs), particularly SDG 7 on affordable and clean energy, SDG 11 on sustainable cities and communities, SDG 12 on responsible consumption and production, and SDG 13 on climate action.

The economic potential of circular energy integration is also significant, creating new business models that transform waste from a cost burden into a productive asset. Industries that adopt this system can reduce the cost of purchasing conventional fuels, lower waste management costs, and even open up additional revenue opportunities through the sale of carbon credits or renewable energy certificates. This transformation encourages the creation of a more resilient and competitive industrial ecosystem, while contributing to the transition to a low-carbon economy, which is currently a global agenda.

Fig. 1. RDF pellet reactor system with residual heat exchanger

The implementation of circular energy integration also creates a multiplier effect in the local economy. The development of waste-to-energy infrastructure creates new jobs, ranging from technical operators and quality analysts to energy system managers. The value chain that is formed involves various sectors, from waste collection and sorting to energy distribution, all of which provide economic added value. In addition, companies that implement these sustainable practices tend to gain a better reputation in the eyes of consumers and investors, increasing the competitiveness of their products in a global market that increasingly prioritizes Environmental, Social, and Governance (ESG) criteria. Thus, circular energy integration is not only a technical solution for waste and energy management, but also a long-term economic strategy that benefits industry players, society, and the environment simultaneously.

### *3.2 Use of RDF pellets*

RDF Pellets involve processing inorganic waste such as plastic, paper, and textiles into high-calorific solid fuel pellets. The material selected as the main raw material in RDF is thermoplastic plastic with a calorific value of more than 20 megajoules per kilogram, namely polyethylene and polystyrene, which have a chlorine content of less than 0.2 percent

(Morfopoulos et al., 2025). The selection of raw materials with low chlorine content is very important to prevent the formation of dioxins and furans during the combustion process (Prariesta et al., 2023). By limiting the carbon monoxide content, dioxin and furan emissions can be reduced in accordance with the standards of Indonesian Minister of Environment Regulation No. 70 of 2016 concerning Quality Standards for Emissions from Thermal Waste Management Businesses/Activities, namely with a dioxin & furan quality standard of 0.1 g/Nm3 and a carbon monoxide standard of 625 mg/Nm3.

The RDF pellet manufacturing process begins with comprehensive waste collection and sorting. Waste from various sources, such as households, commercial establishments, and industries, is collected and separated based on material type. This sorting is a critical stage that determines the final quality of the RDF produced, as materials with high chlorine content, such as PVC, must be separated to meet the specified emission standards. Modern sorting technology involves a combination of manual and mechanical sorting, utilizing sensor-based systems to identify plastic types based on infrared spectrum or material density. An effective sorting process can improve the homogeneity of RDF raw materials and reduce the variability of the final product's calorific value. After sorting, the selected materials enter the mechanical preparation stage, which includes shredding and size reduction. The materials are shredded using a shredder or granulator until they reach a uniform particle size, generally ranging from 10 to 50 millimeters depending on the technical specifications of the pelletizing machine to be used.

This size reduction is important to ensure an optimal densification process and produce pellets with consistent density. Particles that are too large will complicate the compaction process, while particles that are too small can cause problems in the feeding system and reduce process efficiency. At this stage, the material is also cleaned of contaminants such as metal, glass, or other inert materials that can damage equipment or reduce the calorific value of the RDF.

The drying stage is an essential component in the production of high-quality RDF pellets. The shredded material is dried to reduce the moisture content to an optimal level, usually below 15 percent by weight. High moisture content not only reduces the calorific value of RDF but also hinders the pelletization process because excess moisture can cause the pellets to become brittle or not form properly. The drying process can be carried out using various methods such as rotary dryers, belt dryers, or by utilizing waste heat from other industrial processes to improve the overall energy efficiency of the system. Precise moisture content control is essential to ensure consistent RDF quality and facilitate storage and transportation.

The pelletization process is at the heart of RDF Pellets production, where prepared dry material is fed into a pellet mill machine. This machine works by pushing the material through a die or mold with holes of a certain diameter, usually between 6 and 12 millimeters, using high-pressure rotating rollers. The pressure and friction generated during this process produce heat that causes some of the plastic polymers to soften and act as a natural binder, binding the particles into a dense and compact pellet structure. The operating temperature during pelletization typically ranges from 80 to 120 degrees Celsius, sufficient to soften thermoplastics without causing significant thermal degradation. Operating parameters such as feeding speed, roller rotation speed, and the gap between the rollers and the die must be strictly controlled to produce pellets with adequate density, strength, and durability.

Binders or additives can be added to improve interparticle bonding and pellet stability, especially when the raw material composition contains a significant proportion of non-plastic materials such as paper or textiles. Commonly used binders include modified biomass, lignin, or small amounts of synthetic polymers. The selection and dosing of binders must consider their impact on the final calorific value, combustion characteristics, and RDF emission profile. Some RDF formulations also utilize lime or other alkaline materials as additives to neutralize the hydrochloric acid formed during combustion, reducing corrosion on equipment and acid gas emissions.

After the pelletization process, the pellets formed have a high temperature and must be cooled gradually to avoid deformation and ensure perfect hardening. The cooling system can be a counter-flow cooler or horizontal cooler that circulates cold air through the pellet layer. A controlled cooling process is important to lock the pellet structure and increase its mechanical strength. The cooled pellets are then screened to separate fines or fine particles that are not perfectly formed, which can then be recycled back into the process. RDF pellets that meet quality standards are packaged in bags or big bags for storage and distribution.

RDF pellets must be stored in a dry place and protected from moisture to maintain their calorific value and prevent quality degradation during storage. Quality control is a crucial aspect of RDF pellet production to ensure that the product meets the technical specifications required by the end user. Quality parameters that are generally monitored include calorific value, moisture content, ash content, density, mechanical durability, chlorine content, and heavy metal content. Proximate and ultimate analyses are performed periodically to characterize the chemical composition of RDF, while laboratory-scale combustion tests can provide information on combustion behavior and emission profiles. International standards such as EN 15359 for solid recovered fuels provide guidance on classification systems and quality requirements for RDF based on its end use. The implementation of a strict quality management system ensures product consistency and builds user confidence in RDF Pellets as a reliable fuel alternative.

Studies on a national scale have shown the substitution of alternative fuels from plastic waste for co-firing in coal-fired power plants or cement plants (Ismawati et al., 2022). Research conducted by Sharma et al (2025) evaluated the feasibility of RDF as an industrial fuel by performing proximate and ultimate analyses on RDF samples. The results showed that, after waste sorting and processing, RDF has sufficient calorific value and combustionh chacteristics to be used as fuel in the industrial sector. RDF can divert more than 30% of solid waste from landfills and reduce greenhouse gas emissions by around 25%, as well as reduce $SO_2$ and $NO_x$ emissions by more than 15-20% compared to conventional disposal scenarios (Sharma et al., 2025). The use of RDF pellets as co-firing in boilers tends to be stable during combustion and the temperature inside the boiler is maintained (Mulhidin et al., 2022). The thermal conversion of plastic in waste-to-energy facilities with adequate emission control systems has a much lower environmental impact than disposal into the environment, which causes the accumulation of microplastics (Macheca et al., 2024).

The RDF Pellets pathway prevents plastic fragmentation into microplastics through more complete thermal conversion. At high combustion temperatures, plastic polymers undergo complete thermal breakdown into carbon dioxide, water, and hydrochloric acid derived from chlorine and PVC content (Gusty et al., 2023), with solid residues in the form of inert ash that can be used for cement production. This differs from the degradation of plastic in the environment, which produces microplastic particles that then accumulate in the ecosystem (Amanu et al., 2024).

### 3.3 Heat recovery steam generator system

Industrial waste heat represents a significant energy loss in modern production systems. Studies have shown that 20% to 50% of the energy input in industrial processes is wasted as residual heat with a temperature range of 650-230 degrees Celsius (Turek et al., 2024). This phenomenon reflects energy inefficiency that impacts increased operational costs and industrial carbon footprints. In the context of sustainability and energy efficiency, which are increasingly becoming global priorities, residual heat recovery is a crucial strategy for optimizing energy utilization and reducing dependence on primary fuels. Residual heat recovery systems apply heat exchanger technology to extract thermal energy from exhaust gases, then convert it into useful energy output through various processes. This technology not only contributes to energy savings but also supports climate change mitigation efforts by reducing greenhouse gas emissions from additional fossil fuel consumption.

Exhaust gases produced from the combustion of refuse-derived fuel (RDF) have a temperature of more than 200 degrees Celsius, which falls into the category of medium temperature residual heat (Yang et al., 2016). RDF itself is an alternative fuel derived from solid waste processing, which is increasingly being used in industry as a substitute for conventional fuels. The characteristics of RDF exhaust heat at this medium temperature offer significant potential for reuse in various industrial applications. Heat recovery systems at this temperature consist of a heat exchanger as the main component that functions as a heat exchanger, transferring thermal energy from exhaust gases to working fluids such as water or air, so that the residual heat can be reused in production processes or power generation. The design of the heat exchanger is crucial in determining the effectiveness of heat transfer and the overall efficiency of the recovery system.

Many factories and power plants already use Heat Recovery Steam Generator (HRSG) systems to utilize exhaust gas or process gas as a heat source, converting water into high pressure steam that can then be used to drive steam turbines or meet industrial process needs (Pratiwi et al., 2022). HRSG has proven to be a mature and reliable technology in industrial applications, with various configurations that can be tailored to the characteristics of the exhaust gas and specific energy needs. As a concrete example, simulations on an HRSG utilizing the flue gas from a cement plant kiln showed significant heat conversion: high-temperature flue gas was converted into superheated steam, generating approximately 1,141 kW of turbine power with an energy efficiency of around 26.6% (Pratiwi et al., 2022). These results demonstrate that even with moderate conversion efficiency, heat recovery systems can generate substantial power capacity to support plant operations.

At other power generation facilities, particularly Gas and Steam Power Plants/*Pembangkit Listrik Tenaga Gas dan Uap* (PLTGU) that adopt a combined cycle, heat recovery has been shown to dramatically increase overall system efficiency, with heat efficiency values reaching 62.16% under optimal conditions (Santi et al., 2025). This high efficiency is possible because the waste heat from gas turbines, which still has significant energy content, is utilized in HRSG to generate steam for steam turbines, creating an integrated system that maximizes energy extraction from fuel.

One type of temperature sensor that is often used and will also be used in our measuring device is a thermocouple. Accurate temperature measurement is crucial in chemical experiments to understand the solubility behavior of solutes in solutions (Majdi et al., 2024). RTD (Resistance Temperature Detector) is superior to thermocouples in terms of accuracy and stability of temperature measurement, with a precision level of 0.1°C or even higher, while thermocouples are usually only ±1°C to ±2°C. On the other hand, based on research conducted by (Priambudi & Kurniawan, 2021), the use of PT100 RTD sensors is specifically designed for extreme temperatures and is less accurate in reading temperatures below 100°C (Priambudi & Kurniawan, 2021). The Resistance Temperature Detector (PT100) is used in the temperature range of -200°C to 650°C (Sumarkantini, 2018).

Based on the results of research conducted by Sarkar (2018), the results of testing several temperature points using RTD with a two-wire configuration for the temperature range (-100 °C to 100 °C) consisting of a microcontroller unit (MCU) and an analog-to-digital converter, a voltage source, and the RTD resistance value were calculated based on the voltage measured across the RTD and the current sensing resistor. The test results showed that the accuracy of the temperature measuring device could reach ±0.02 °C. However, challenges in the RTD measurement circuit showed limitations in measuring current. This is due to self-heating effects, resistance in the circuit, and solder wire resistance. Errors in each component are related to tolerance, temperature coefficient, linearity, etc. This study suggests adding three reference resistors to the constructed system to obtain the maximum value calculated by Monte Carlo analysis. The proposed method for RTD resistance from 600 Ω to 1400 Ω with a step size of 100 Ω is shown in the table. The Pt100 RTD is a type of RTD that has fairly high accuracy because it is a temperature-sensitive resistor, where the resistance value will change according to temperature changes. Therefore, RTDs are transducer components that can be used as sensors in automation or control processes (Komalasari & Saragih, 2024).

### 3.4 Generator

Thermoelectric devices consist of electronic components made of solid materials or semiconductors that can produce the Seebeck effect and the Peltier effect. The Seebeck effect occurs when a thermoelectric device receives a temperature difference as input, thereby producing electricity as output (Ananda et al., 2020). This module consists of several matrices containing a number of conductor connections arranged in series and parallel. The series conductor arrangement serves to increase the module's output voltage, while the parallel arrangement serves to increase the output current of the thermoelectric module (Putra et al., 2019).

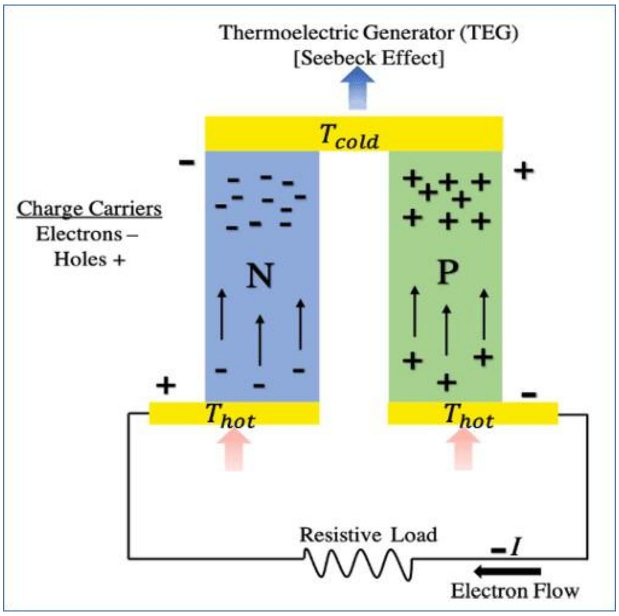

Fig. 2. Principle of Operation of TEG
(Jouhara et al., 2021)

The design of an optimal system, especially a transmission network, when included in an optimization problem, is greatly influenced by modeling. The optimal solution avoids the construction of closed loops in the transmission network. Otherwise, the system will have a more connected network, which may be less practical or operable in the field (Gao et al., 2025). Thermoelectric devices are essentially solid-state elements that can work in two directions: as heat pumps when electrified, or as power generators when subjected to temperature differences. These thermoelectric devices are controlled by two main phenomena, namely the Peltier effect and the Seebeck effect. Thermoelectric devices are divided into two types, namely Thermoelectric Coolers (TEC) and Thermoelectric Generators (TEG). Both types of thermoelectric elements can convert heat energy into electricity and vice versa. Thermoelectric elements function to convert electricity into heat based on the Peltier effect principle, which is applied in Thermoelectric Coolers (TEC). When an electric current is passed through a p-type and n-type material junction, heat is absorbed on one side of the junction and released on the other side. The side that absorbs heat becomes cold, which is used to cool electronic components, while the other side becomes hot and must be dissipated with a heat sink or liquid cooler. Meanwhile, to generate electricity from heat energy, thermoelectric elements utilize the Seebeck effect, which I used in Thermoelectric Generators (TEG) (Rifky et al., 2024). The TEG system works such that if both ends of the thermoelectric circuit are made to have different hot and cold temperatures, an electrical potential difference will arise between the ends. This potential difference generates an electric current and power when connected to a load, making it suitable for utilizing waste heat from exhaust gases, hot surfaces, or hot fluids. Broadly speaking, the difference between TEC and TEG is that TEC uses electricity to transfer heat (Peltier effect), while TEG utilizes temperature differences to generate electricity (Seebeck effect), even though both use thermoelectric elements that are essentially the same.

Using the TEG method to recover heat stored in hot fluids (in this case, air), the heat is first absorbed by a heat exchanger (HEX) in the form of conjugate heat transfer, then transferred to a thermoelectric module (TEM) to generate electricity. The heat is gradually removed by the cooling fluid (water) in the cooling unit (Jouhara et al., 2021). Based on the results of research conducted by Andrapica et al. (2017), the more thermoelectric modules used during testing, the greater the power generated. The HEX walls receive heat through a combination of convection and conduction, which is called conjugate heat transfer. So, in general, the system works as follows: hot air resulting from RDF heating in the boiler enters the HEX, and the residual heat flows to the TEG module. This heat is then converted into electricity by the Seebeck effect, while the residual heat that cannot be reused is carried away by the cooling water through the chimney.

Thermoelectric generators (TEGs) are a promising technology used to reduce gas emissions and thus control global warming. TEGs are based on the Seebeck effect through the direct, environmentally friendly conversion of thermal energy into electrical energy. TEGs have several advantages besides having no environmental impact, no moving parts, no circulating fluids or chemicals, flexibility in size and shape, and durability (Olabi et al., 2022). The thermoelectric module then converts the temperature gradient into electricity through the Seebeck effect. The pair of p-type and n-type semiconductor elements in the module will experience a charge carrier flow from the hot side to the cold side, creating an electrical potential difference between the two ends of the circuit. When connected to a load, this potential difference generates an electric current and power. Not all of the heat that passes through the module can be converted into electrical energy. The remaining heat is absorbed by the water flowing in the cooling unit, then discharged along with the water flow or released into the atmosphere through a cooling tower/chimney. This cooling water keeps the temperature on the cold side of the module low so that ΔT does not decrease, because a decrease in ΔT will directly reduce the voltage and power generated.

### *3.5 Modified emission sensor*

A continuous emission monitoring system is an essential component to ensure environmental compliance and public acceptance of waste-to-energy facilities. The emission monitoring system places sensors and measuring devices directly on the stack gas, as the stack is the final point of gas discharge (Susanto et al., 2020). Experimental studies on RDF–coal co-firing in combustors show that combustion processes with RDF can produce pollutant emissions, including gaseous pollutants and HCl, as well as potential PCDD/F due to incomplete combustion or high temperature and chlorine conditions (Xu et al. 2025). This system integrates gas analyzers for dioxins, furans, and carbon monoxide CO). Dioxin and furan monitoring is performed using High Resolution Mass Spectrometry (HRMS) integrated with a High Resolution Gas Chromatography (HRGC) system to accurately separate and identify each congener (Roy et al., 2002). Monitoring of dioxins and furans with the HRGC–HRMS system basically consists of three major stages: separation, mass detection, and highly selective quantification.

In High Resolution Gas Chromatography (HRGC), sample extracts, such as water that has undergone extraction and purification, are injected into a specially polarized capillary column. The column separates dozens of dioxin/furan congeners based on volatility and interaction with the stationary phase, so that each exits the column (retention) at a different time. The temperature in the GC oven is set with a highly precise temperature ramp program so that congeners with similar structures remain well separated (high resolution).

The gas exiting the GC column enters the High Resolution Mass Spectrometer (HRMS), which generally uses electron impact (EI) or chemical ionization. In the ion source, dioxin or furan molecules are ionized into specific charged ions, which are then separated based on their mass-to-charge ratio using a high-resolution analyzer (e.g., magnetic sector or high-resolution time-of-flight).

The very high mass resolution allows the instrument to distinguish target ions from matrix interferences that have nearly the same mass, making the identification of each congener very specific. These emission parameters are continuously monitored using an infrared or electrochemical analyzer (Gunawan et al., 2025). The data acquisition system uses the Industrial Internet of Things with edge computing for real-time data processing for centralized monitoring dashboards, data analysis, and reporting to regulators (Fatimah, 2025). With this combination of HRGC and HRMS, dioxin and furan monitoring meets international regulatory requirements.

In addition, a continuous emission monitoring system at coal RDF facilities should ideally be integrated with a comprehensive environmental management scheme, such as setting emission limit alarms, rapid response procedures, and independent verification mechanisms. Continuously recorded emission data can be used to identify long-term trends, recalibrate combustion operation set points, and evaluate the effectiveness of pollution control technologies, such as bag filters, scrubbers, or selective catalytic reduction. When certain emission thresholds are exceeded, the system can trigger automatic alerts for RDF load reduction, combustion air distribution adjustments, or even temporary shutdowns until the cause is resolved. Thus, emissions monitoring is not only a reporting tool, but also a process control instrument that supports the safe, transparent, and globally compliant operation of waste-to-energy facilities.

### *3.6 System sustainability*

The implementation of a combination of solid waste utilization and heat recovery still faces a number of technical, environmental, and economic challenges. From a technical perspective, waste characteristics (moisture content, calorific value, ash composition, contaminant content) vary greatly, affecting combustion efficiency or thermochemical processes and boiler stability (Lombardi et al., 2015). The performance of this system can decline over time, for example due to fouling, corrosion, or a decrease in evaporator performance, as reported in the HRSG unit at the Jawa Satu Power PLTGU facility (Putra, 2024). In addition, environmental aspects also need to be considered: thermal conversion of waste (incineration/gasification) can cause emissions of gases, ash, residues, or pollutants if not equipped with an emission control system and ash management (Wahditya et al., 2025). From an economic perspective, the initial investment costs (special boiler equipment, HRSG, pyrolysis/gasification systems, emission controls) and operational costs can be high, and the system needs to be designed to be economical in the long term.

Other operational challenges include the need for skilled labor to operate and maintain these complex systems. Ongoing training is necessary to ensure operators can handle the variability in fuel quality from waste, troubleshoot the heat recovery system, and respond quickly to abnormal conditions. System integration also requires modifications to existing infrastructure, which can disrupt normal plant operations during the installation period. Coordination between the waste treatment unit and the main production system is crucial to ensure continuous energy availability without disrupting the manufacturing process.

From a regulatory perspective, the implementation of this system must comply with various emission standards and strict environmental licensing requirements. The complex and time-consuming permitting process can delay project implementation and increase administrative costs. Regular emission monitoring and reporting also add to the operational burden, although this is essential to ensure compliance with environmental regulations. In addition, future regulatory changes may affect the economic viability of installed systems, requiring design flexibility to accommodate stricter standards.

The circular energy integration system contributes measurably to the Sustainable Development Goals (SDGs) with specific indicators. It is well established that sustainability and energy management go hand in hand with the concept of a circular economy (Seljak et al., 2023). For SDG 7 on affordable and clean energy, RDF Pellets can be used to substitute coal with lower energy costs and can improve energy access, especially in industrial areas that are not connected to the main electricity grid. The implementation of waste-to-energy systems also contributes to the diversification of the national energy portfolio, reduces dependence on imported fossil fuels, and increases local energy security.

For SDG 9 on industry, innovation, and infrastructure, the implementation of advanced control systems, Internet of Things-based monitoring, and innovations in converting waste into energy (Wahditya et al., 2025). Digital technology enables real-time optimization of energy conversion processes, predictive preventive maintenance, and integration with smart grids for more efficient energy management. The development of integrated waste collection and processing infrastructure also creates a more resilient and sustainable industrial ecosystem.

For SDG 12 on responsible consumption and production, this system promotes the reduction of waste to landfills and encourages the application of the 3R (Reduce, Reuse, Recycle) principle at the industrial level. The transformation of waste into an energy resource changes the linear paradigm to a circular one, where the output of one process becomes a valuable input for another process. For SDG 13 on climate action, measurable emission reductions contribute directly to national emission reduction targets (United Nations, 2015). Substituting fossil fuels with RDF and utilizing waste heat reduces $CO_2$ emissions, while diverting waste from landfills reduces methane emissions, which have a global warming potential 25 times higher than $CO_2$.

## 4. Conclusions

The integration of the Circular Energy system through the use of RDF pellets and residual heat recovery technology has proven to be a strategic approach to reducing industrial emissions and optimizing wasted energy. RDF pellets based on low-chlorine thermoplastic plastics are capable of producing high calorific value while minimizing the formation of dioxins, furans, and microplastics during the combustion process. This system has stable thermal performance, making it a potential replacement for coal as an energy source for industrial processes.

On the other hand, residual heat recovery technology through heat exchanger an Heat Recovery Steam Generator (HRSG) configurations can recover more than 80% of waste heat, converting it into new energy output in the form of steam or electrical energy that can be reused in industrial processes. The integration of sensor-based emission monitoring systems with a real-time approach is key to ensuring compliance with environmental quality standards and improving operational reliability. Overall, circular energy integration contributes significantly to supporting the implementation of national industrial decarbonization, reducing inorganic waste, and increasing energy utilization efficiency. This concept not only has an impact on technical and environmental aspects but also provides social and economic benefits and directly supports the achievement of SDGs 7, 9, and 13 as steps towards a sustainable and low-emission industrial system.

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## Author Contribution

Conceptualization, K.A.K., Q.A. and Y.Y.; Methodology, K.A.K., and Q.A.; Software, Y.Y.; Validation, K.A.K., Q.A. and Y.Y.; Formal Analysis, K.A.K., Q.A.; Writing – Original Draft Preparation, K.A.K.; Writing – Review & Editing, K.A.K., Q.A. and Y.Y.

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The authors declare no conflict of interest.

## Declaration of Generative AI Use
During the preparation of this paper, the author used AI assistance in the form of Claude AI and Chat GPT. The image concept was generated with the assistance of AI; however, the final images were created using Corel software.

## Open Access

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