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Performance Improvement of Sand-Based Batteries using Sea Sand and Metal Waste as an Alternative Energy Storage System

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Abstract: The shift to renewable energy faces the challenge of intermittency, which requires effective Energy Storage Systems (ESS). Sand-Based Thermal Energy Storage (TES) presents a cost-effective and environmentally friendly solution, although it suffers from the low thermal conductivity of sand. This research seeks to enhance the thermal efficacy of sand batteries by incorporating waste iron shavings from lathes as a composite material and examining its suitability for pilot-plant scale heating. A 96-liter sand battery container was used with varying mixtures of iron waste at 0%, 10%, 20%, and 30% relative to the volume of sea sand. The charging process used a 4000-watt power supply for simulation and 4000 Wp solar panels for validation. The discharge process was implemented to provide heat to a copra drying oven. The findings indicate that incorporating waste iron significantly improves the heat transfer rate and temperature uniformity during charging. The composition with 30% iron (P-30) demonstrated the most favorable thermal properties. During discharge tests, the system maintained the copra drying oven temperature within 56-57°C for over 12 hours, meeting the required drying temperature standards. This study proves that sand batteries with a waste iron composite represent an effective, cost-effective, and sustainable TES solution for thermal applications in the context of renewable energy.

Keywords: Energy Storage System (ESS), Iron Waste, Renewable Energy, Sand Battery, Thermal Energy Storage (TES)

1. Introduction

The transition from fossil fuels to renewable energy is accelerating due to the global energy crisis and environmental concerns [1]. Renewable energy sources such as solar and wind are intermittent, depending on climatic conditions [2]. The advancement of Energy Storage Systems (ESS) is crucial for reconciling fluctuating energy supplies with stable demand [2], [3]. Efficient energy storage systems enhance grid stability and facilitate the greater integration of renewable energy sources [1].

By leveraging thermal energy storage, Indonesia can

increase its use of renewable energy, particularly solar, to address its energy challenges. The development of ESS in Indonesia will assist the government in achieving its renewable energy mix target of 17% by 2025[4]. Consequently, integrating energy storage technology is vital for the national sustainable energy strategy. It is essential to align these technological storage advancements with national energy policies and government-set targets [5].

Among various ESS technologies, Thermal Energy Storage (TES) is notable for its low cost. Sand is an attractive TES material due to its availability, cost-effectiveness, environmental benefits, and high melting point. This system helps reduce dependence on fossil fuels and promotes a sustainable energy mix [6]. The implementation of thermal energy storage can enable Indonesia to harness its renewable energy potential and enhance electricity diversification [7]. Energy diversification through thermal storage technology improves system efficiency and increases energy supply security in Indonesia [8].

The main drawback of sand as a thermal medium is its low thermal conductivity [9]. This limitation reduces the heat transfer rate, impacting system efficiency [10]. Several studies have attempted to mitigate this issue by combining sand with materials that exhibit higher thermal conductivity [2]. Evidence suggests that sand composites augmented with conductive materials, such as copper foam or graphite, can improve thermal energy storage efficiency [11]. Nevertheless, additional research is needed to investigate diverse material combinations and methodologies to further optimize the performance of thermal energy storage systems [1][12].

This study proposes enhancing the thermal conductivity of sea sand by incorporating waste iron shavings from lathe operations [3]. The application of this waste can improve the thermal efficiency of sand batteries while lowering metal recycling costs [13]. Using waste iron shavings as an additive in the sand mixture presents a novel strategy for improving thermal energy storage efficiency [10][14]. The integration of waste iron shavings in sand composites fosters the development of more effective materials, thereby promoting industrial sustainability and environmentally conscious thermal energy storage solutions [15]. This innovation aligns with initiatives aimed at addressing social and economic challenges, as previously mentioned regarding the adoption of sustainable materials [6]. These advancements not only aim to improve thermal energy storage efficiency but also to reinforce the principles of environmentally sustainable development intended to reduce adverse environmental and social impacts [5][16].

For decades, graphite has been the primary material in Li-ion battery (LIB) anodes. The search for high-capacity anode materials for LIBs has led to growing interest in silicon (Si) as a potential replacement for graphite [17]. Indonesia's high solar irradiation level, averaging 4.8 kWh/m²/day, presents a significant opportunity to utilize solar power to meet rising energy demands [18]. The highlighted advantages include replacing fossil fuel power plants with solar energy, reducing carbon dioxide emissions, and decentralizing energy generation [19]. This study aims to analyze the characteristics of a sand battery made from sea sand with varying mixtures of iron waste—0%, 10%, 20%, and 30%—to determine the effect on its thermal energy storage and release capabilities. A primary focus is to determine the optimal mixture composition for the best performance during the energy charging process, evaluated in terms of temperature stability and heat storage capacity. Additionally, this research analyzes the performance of the energy discharging process by applying the sand battery to heat a copra drying oven, which requires a stable temperature in the 55–60°C range for the drying process to be effective and efficient.

2. Research Methodology

This research was conducted at the Renewable Energy Engineering Laboratory, Politeknik Negeri Sriwijaya and at PT. Kilang Pertamina Internasional Refinery Unit 3 Plaju, from July 2024 to May 2025.

2.1. Materials and Equipment

The primary materials used consisted of sea sand sourced from Palembang and waste iron shavings from a local lathe workshop. X-ray Diffraction (XRD) analysis of the sea sand revealed a dominant Calcium (Ca) content of 28% and an Alpha-Iron (α-Fe) content of 23%. Laser-Induced Breakdown Spectroscopy (LIBS) analysis identified the waste iron as low-carbon steel with an Iron (Fe) content of 98.19%.

The main equipment included:

- A sand battery container with dimensions of 60 cm x 20 cm x 80 cm (96-liter total volume).
- Four 500W (48 VDC) tubular heater units.
- A power supply system consisting of a 4000W power supply for simulation and 16 solar panel units (250 Wp each, 4000 Wp total) for practical testing.
- Temperature measurements were taken using nine K-type thermocouples connected to a temperature recording system.

2.2. Experimental Procedure

The research began with a sample preparation stage, where four composition variations were prepared based on volume ratio: pure sand (P-0), and mixtures of sea sand with 10% iron waste (P-10), 20% (P-20), and 30% (P-30). The bulk densities were 1.70 kg/liter for sand and 2.75 kg/liter for iron waste.

In the charging process, each sample was heated inside the container using the tubular heaters until it reached a temperature of 500°C. The temperature rise profile at three different points (right side, middle, and left side) was recorded continuously using the temperature recorder.

Subsequently, in the discharging process, the stored thermal energy was utilized to heat a 10-liter copra drying oven via a copper tubing heat exchanger. The oven's temperature was monitored for 12 hours to evaluate the sand battery's ability to maintain a stable operating temperature within the 55–60°C range.

3. Results and Discussion

This research on the sand battery investigated two primary materials: sea sand and an iron mixture. The composition of

these materials was assessed through laboratory analysis. The sea sand was analyzed using X-Ray Diffraction (XRD) at the laboratory of the Faculty of Mathematics and Natural Sciences, Sriwijaya University. The iron mixture was evaluated with Laser-Induced Breakdown Spectroscopy (LIBS) at PT. Kilang Pertamina Internasional RU III Plaju. The findings from the analysis of both materials are presented below.

Table 1. *Sea Sand Composition*

Sample	Composition	Unit	Test Result
Sea Sand	*SiO_2*	%	16
	Ca	%	28
	Sr	%	15
	Mo	%	5
	Alpha-Fe	%	23
	Mn	%	11
	Yb	%	1.1
	unknown	%	0.9

The sea sand, sourced from Lampung, has a distinctive chemical profile and significant industrial utility. The high concentrations of calcium and iron, along with trace metals like molybdenum, strontium, and ytterbium, suggest potential applications in the metallurgical sector, specialty construction, and rare earth element research. Additionally, the silica content indicates possible use in construction materials.

Table 2. *Composition of Iron Mixture from Lathe Waste*

Sample	Composition	Unit	Test Result
Lathe machine iron waste	*Fe*	%	98.19
	Mn	%	1.36
	Si	%	0.24
	Ni	%	ND
	C	%	0.04
	Cr	%	0.04
	Cu	%	0.04
	Al, Nb, Ti, Pb, V	%	ND

The iron waste from the lathe machine was sourced from a workshop in Palembang city between January and March 2025. This waste primarily consists of iron with minimal manganese and trace elements, indicating its derivation from the machining of low-carbon steel. The negligible presence of other alloying metals makes it unsuitable for high-engineering or corrosion-resistant applications. Nevertheless, the material holds a significant promise for recycling into secondary iron/steel products or for use as a basic structural material.

Table 3. *Volume and Weight of Sand and Iron Mixtures*

Mixture Percentage	Initial Sample	Sand Volume (liter)	Iron Volume (liter)	Sand Weight (kg)	Iron Weight (kg)	Total Weight (kg)
Sand, 0%	P-0	96	0.0	163.2	0.0	163.2
Sand, 10% iron	P-10	86.4	9.6	146.9	26.4	173.3
Sand, 20% iron	P-20	76.8	19.2	130.6	52.8	183.4
Sand, 30% iron	P-30	67.2	28.8	114.2	79.2	193.4

Incorporating a higher volume percentage of iron waste significantly increases the total weight of the mixture. This phenomenon arises from the higher density of iron waste compared to the sea sand (2.75 kg/L versus 1.7 kg/L). A 48 VDC, 4,000-watt power supply facilitated the simulation of the sand battery charging to ascertain its characteristics before direct connection with the 4000 Wp solar panels. The charging load consisted of four 500-watt tubular heaters, for a total of 2000 watts. The following table illustrates the performance metrics of the power supply.

Table 4. *Performance of the 4-Channel 4000-Watt 48 VDC Power Supply*

Performance	Ch-1	Ch-2	Ch-3	Ch-4
Output Voltage (no load)	48 VDC	48 VDC	48 VDC	48 VDC
Current (no load)	0.1 A	0.1 A	0.1 A	0.1 A
Heater Temperature	500 °C	500 °C	500 °C	500 °C
Output Voltage (with load)	48 VDC	48 VDC	48 VDC	48 VDC
Current (with load)	11.0 A	10.5 A	10.8 A	10.7 A

- Output Voltage Stability: All channels showed a stable output voltage of 48 VDC, indicating reliable performance under various conditions.
- Very Low No-Load Current: The no-load current per channel was 0.1 A, reflecting high efficiency and minimal leakage.
- Uniform Heating Temperature: The heater temperature uniformly reached 500°C across all channels, demonstrating consistent thermal performance and equitable power distribution.

Figure 1. *4000-watt 48 VDC Power Supply*

The solar installation consists of 16 panels; each rated at 250 Wp. These panels are configured in two series of eight, producing a voltage of 96 VDC. Subsequently, the two series configurations are paralleled to supply the tubular heaters operating at 48 VDC, totaling 1000-watts at 96 VDC. Below is the performance table for the 4000 Wp solar panel system.

Table 5. *Performance of the 4000 Wp Solar Panel System*

Performance	Channel 1	Channel 2
Output Voltage (no load)	125 VDC	126 VDC

Performance	Channel 1	Channel 2
Current (no load)	0.0 A	0.0 A
Heater Temperature	450 °C	450 °C
Output Voltage (with load)	85 VDC	86 VDC
Current (with load)	9.4 A	9.5 A

Based on the performance testing of the 4000 Wp solar panel system with two channels, the no-load output voltage was 125 VDC for Channel 1 and 126 VDC for Channel 2, indicating compliance with voltage specifications under no-load conditions. The recorded no-load current was 0.0 A on both channels, indicating the absence of current flow due to the open circuit.

Figure 2. *4000 Wp Solar Panel System - 16 panels @ 250 Wp*

The optimal performance of the sand battery was assessed during the charging phase with varying iron mixture percentages of 0%, 10%, 20%, and 30%. To analyze the fundamental thermal properties of the thermal energy storage media, a 4000-watt tubular heater served as the energy source, simulating the charging process that would later utilize the 4000 Wp solar panels with the 30% iron mixture.

Figure 3. *Sand Battery and Copra Heating Oven*

The charging experiment on the P-0 sand battery serves as a baseline to assess the performance of thermal energy storage based on unmodified sand. The process evaluated temperature distribution at different material locations during heating. This study investigated the thermal response of pure sand, heated by a 4000-watt power supply, and analyzed the temperature patterns at three distinct points: right (T1), middle (T2), and left (T3).

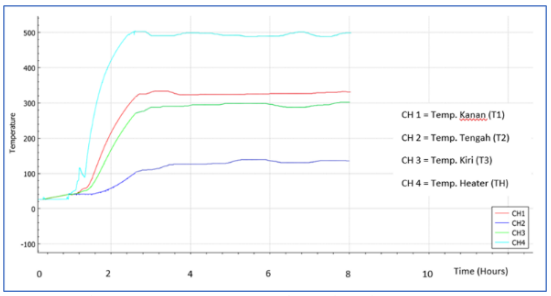

Figure 4. *Charging Temperature of Sand without Iron Mixture (P-0)*

The charging process for sand without iron (P-0) showed a significant temperature gradient, indicating a need for improved heat distribution efficiency or heater design for uniformity. Heating of sand mixed with 10% iron (P-10) was then conducted to assess the impact of metal content on temperature distribution, aiming to analyze the thermal response of metal-infused sand versus pure sand with a 4000-watt heating source.

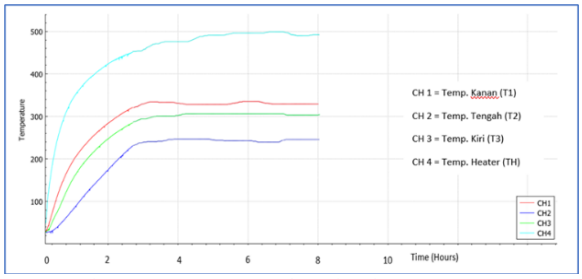

Figure 5. *Charging Temperature of Sand with 10% Iron Mixture (P-10)*

This investigation aimed to assess the effect of incorporating 20% iron into the sand on its thermal absorption and distribution capabilities during charging. The goal was to analyze the improvement in thermal efficiency relative to pure sand and the 10% iron composition using a 4000-watt heating source.

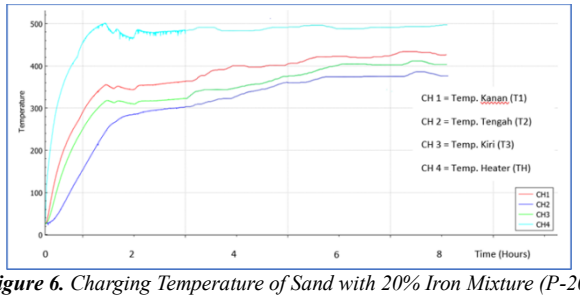

Figure 6. *Charging Temperature of Sand with 20% Iron Mixture (P-20)*

The sand composition with 20% iron (P-20) demonstrated superior thermal performance relative to pure sand and the 10% iron mixture. This configuration achieved higher temperatures and enhanced uniformity, making it more effective for thermal applications requiring rapid and consistent heating.

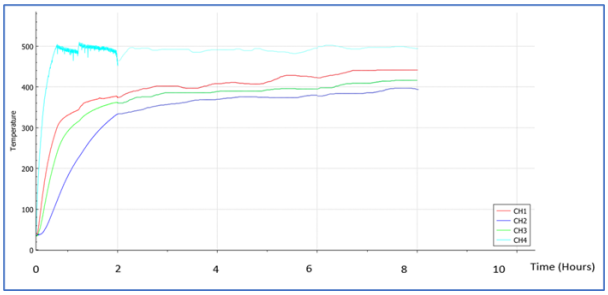

Figure 7. *Charging Temperature of Sand with 30% Iron Mixture (P-30)*

The incorporation of 30% iron (P-30) into the sand significantly enhanced thermal conductivity, evidenced by a more pronounced temperature rise. After two hours, the channels reached thermal equilibrium, signifying a stable thermal state.

This experiment contributes to the research of sand battery technology as a thermal energy storage (TES) system. Within this framework, sand serves as the heat storage medium, heated by a renewable energy source, specifically solar panels. The material used was designated as P-30. The captured solar energy was converted into electrical energy, then used to heat the heating elements. The generated heat was transferred to the sand medium, with temperature variations recorded at various points (right, middle, left) and at the heat source (heater).

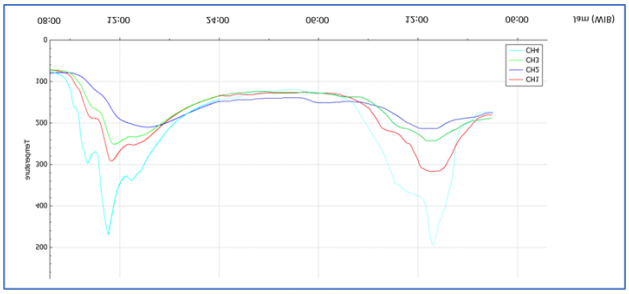

Figure 8. *Charging Sand with 30% Iron Mixture (P-30) with 4000 Wp Solar Panels*

The graph depicts temperature fluctuations of four channels during the observation period of May 29-30, 2025, with CH1–CH3 showing material temperatures and CH4 indicating the heater temperature.

Discharging the sand battery involves the release of previously stored thermal energy after the charging phase, which is essential for reusing the thermal energy in applications like drying, air heating, or power generation. A 10-liter copra heating oven served as the pilot plant for this research. The objective was to evaluate the efficacy of the sand battery in maintaining the optimal oven temperature for the copra drying process (55-60°C).

Figure 9. *Discharging Process of the Sand Battery with the Copra Heating Oven*

Temperature monitoring occurred during the copra drying process for 12 hours for the main components: the sand battery, the heat exchanger (input and output), and the oven temperature. Initially (hour 0), the sand battery temperature was 380°C, decreasing to 223°C by the 12th hour. This decrease also impacted on the heat exchanger output temperature, which dropped from 165°C to 84°C. In contrast, the heat exchanger input temperature remained consistent, fluctuating between 24-27°C.

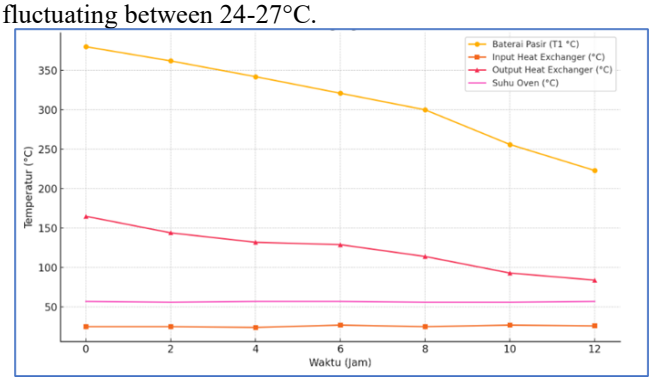

Figure 10. *Sand Battery Discharging - Trial 1*

The oven temperature was consistently maintained at 56-57°C despite the dropping temperature of the heat source. This demonstrates the system's ability to maintain the oven temperature within the optimal standard range for copra drying (55-60°C). The stable oven temperature ensures the maintenance of copra drying quality throughout the processing duration.

The graph illustrates a gradual decrease in the sand battery temperature from 375°C at hour zero to 216°C at hour twelve. Concurrently, the heat exchanger output temperature reduced from 160°C to 75°C, reflecting the reduction in heat transfer to the system. Notably, despite the decreasing temperature of the storage medium, the oven temperature remained stable within 56-57°C, adhering to the drying standard of 55 to 60°C.

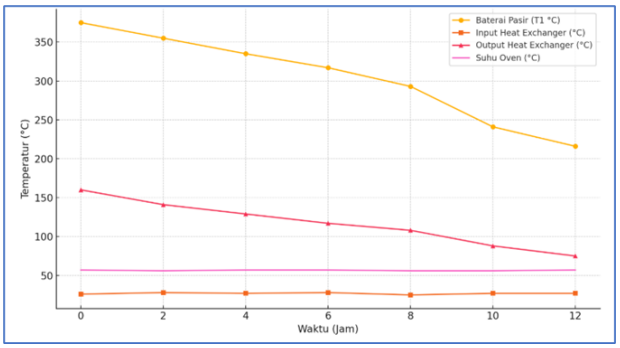

Figure 11. *Sand Battery Discharging - Trial 2*

At the initiation of the observation (hour 0), the sand battery temperature was 380°C, signifying maximum thermal energy absorption. Over the next 12 hours, the battery temperature decreased to 210°C. This reduction was steady, indicating sustained heat dissipation from the system. The heat exchanger output temperature, which indicates heat transfer from the sand battery, decreased from 163°C to 82°C. In contrast, the heat exchanger input maintained a consistent

temperature between 26-28°C, reflecting the initial ambient temperature before heat absorption. Notably, the oven temperature for drying remained stable at 56-57°C, within the standard drying range for copra (55-60°C).

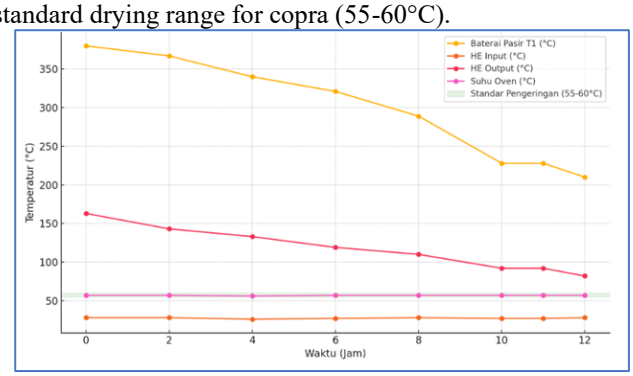

Figure 12. Sand Battery Discharging - Trial 3

The discharging process of the sand battery demonstrates that sand effectively stores and gradually releases thermal energy over an extended period. The system can maintain the required drying temperature within the necessary limits for up to 12 hours, despite the gradual decrease in temperature post-charging. This indicates that the heat radiated by the sand battery is efficiently utilized for drying organic materials, such as copra, without requiring additional external energy.

4. Conclusion

The research results show that the addition of waste iron shavings to sea sand significantly improves the thermal conductivity and heat storage capacity of the sand battery system. The mixture of 30% iron proved to provide the most optimal performance during the charging process, characterized by achieving higher temperatures and a more uniform heat distribution.

The system was also successfully applied for heating a copra drying oven. During the 12-hour discharging process, the oven temperature was stably maintained in the 56–57°C range, which aligns with the optimal requirements for copra drying. This study proves that a sand battery based on metal waste is technically and economically feasible as a reliable, low-cost, and sustainable Thermal Energy Storage (TES) solution. Furthermore, it supports the principles of a circular economy through the utilization of industrial waste.

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