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Development and Performance Evaluation of a Micro-Scale RDF Briquette–Fueled Steam Power Prototype

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Abstract. Plastic waste is a major environmental problem in Indonesia due to its non-biodegradable nature. One innovative solution is converting waste into energy using Refuse-Derived Fuel (RDF) briquettes for small-scale power generation. This research designed and tested an RDF-based micro power plant prototype using briquettes composed of 80% dry organic biomass and 20% plastic for safe and stable combustion. The prototype consists of a combustion chamber, heat exchanger, impulse-type micro steam turbine driven by low-pressure steam, and a 12V low-speed DC generator. Performance was evaluated through temperature, voltage, current, power output, and efficiency measurements. The highest performance was achieved using 500 g of RDF, producing 0.02 A, 0.7 V, and 0.014 W at 135°C over 20 minutes, with an efficiency of 2.69×10^{-6}%. Although efficiency was very low, the study demonstrates proof-of-concept feasibility and provides a baseline for future optimization of thermal and energy conversion efficiency.

Keywords: refuse-derived fuel (RDF), briquettes, micro-scale steam turbine, waste-to-energy, prototype power generation.

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1. **Introduction**

The increasing volume of plastic waste in the world can cause an alarming ecological emergency[1,2]. The short life cycle of plastic, due to it being a single-use item, increases the accumulation of plastic in the environment [3,4]. About two-thirds of global plastics have a life cycle of less than a month. It is estimated that global plastic waste accumulated around 6.30 billion tons from 1950 to 2015, and around 80% of plastic accumulates in the natural environment. The generation of plastic waste in 2016 reached around 242 million tons. Therefore, even old plastic can still be found in nature. Based on predictions, the accumulation of plastic waste in 2035 will be equivalent to the number of fish in the ocean. The classification of plastic waste based on its origin is divided into municipal solid waste and agro-industrial waste [5]. Based on data from the Indonesia Solid Waste Association, the amount of plastic waste in Indonesia is 5.4 million tons per year or 14% of total waste production. Data from the Jakarta Regional Environmental Management Agency (BPLHD) in 2014 stated that in the DKI Jakarta area, as much as 13% of the 6,000 tons of waste per day was plastic waste [6]. Environmental pollution can occur from the increasing amount of plastic waste [7]. Naturally, plastic waste is very difficult to decompose. In soil, plastic waste takes 20 to 100 years to decompose [8]. Plastic waste also causes problems in land waters because it can reduce fertility, harm animals in the waters, and disrupt coastal ecosystems [9,10]. Waste management is an urgent need to maintain environmental sustainability and recover value from waste [1,2].

Apart from the waste problem, the consumption of electrical energy needs is also increasing every year [11]. Electrical energy needs in Indonesia according to data from PLN in 2022 show that electricity consumption in industry is 88,483.30 GWh (32.32%), household consumption is 116,095.41 GWh (42.41%), electricity consumption for business is 50,532.19 GWh (18.46%), and 18,650.58 GWh (6.81%) for social, government and government buildings. public street lighting [12]. Electricity distribution data from PLN to the public during the 2014-2019 period is always increasing. To produce electricity, fuels such as coal, gas, diesel and uranium are needed, which are limited in availability [13,14]. The higher the consumption of electrical energy, the less electrical energy sources there are because the availability of the primary source of production, namely coal, is currently running low [15].

One solution to dealing with waste and energy needs can be done by making Refuse-Derived Fuel (RDF). RDF can be produced from municipal solid waste processing [16]. Plastic waste can be used as RDF for fuel purposes. RDF is the product of a separation process that separates flammable solid waste from non-combustible solid waste [17]. The use RDF as a partial replacement for coal in PLTUs through a co-firing scheme has proven effective in reducing emissions and supporting the energy transition in Indonesia. The implementation of RDF helps overcome the problem of municipal waste by converting it into a renewable energy source [18].

Recent developments in micro-scale waste-to-energy (WtE) systems have primarily focused on thermochemical conversion technologies, including pyrolysis, gasification, and direct combustion coupled with steam-based power generation. Pyrolysis and gasification can produce syngas or liquid fuel with lower particulate emissions and higher conversion efficiency. However, these technologies require precise control of temperature, oxygen availability, and feedstock composition. Researchers chose to use a direct combustion-based system integrated with a steam generator using Waste-Derived Fuel (RDF) because this combustion system utilizes waste as fuel with varying composition, particle size, and moisture content.

RDF briquette produce uneven flame characteristics, fluctuating combustion temperatures, and residue formation. Steam-based microturbine system which operate within narrow pressure and temperature ranges, require stable and continuous thermal input to maintain efficiency and mechanical reliability. Achieving sufficient and steady steam generation from RDF combustion is difficult due to heat losses, limited boiler capacity, pressure instability, and turbine stress. This research focuses on demonstrating proof-of-concept performance while identifying key technical constraints related to fuel variability, combustion stability, and low-temperature power generation. This study provides empirical output mapping versus briquette mass, and identifies key performance-limiting factors related to pressure, leakage, and turbine design. This study quantitatively evaluates the performance limits of a laboratory-scale RDF briquette-fired steam power plant prototype by determining the achievable electrical output under controlled combustion conditions and identifying the dominant subsystems contributing to overall energy losses.

2. **Methods**

The experimental setup consisted of several mechanical, thermal, and electrical components assembled to form a small-scale steam-based power generation prototype. The combustion chamber was constructed using a steel biomass stove with an internal diameter of approximately 18–20 cm and a wall thickness of about 1.0–1.5 mm. This stove served as the primary heat source for burning the prepared briquettes and transferring thermal energy to the boiler. Steam generation was carried out using a pressure cooker–type boiler fabricated from stainless steel, with a nominal capacity of 4 L and an estimated wall thickness of approximately 2–3 mm. The boiler and connected steam line were operated without external thermal insulation, which resulted in unavoidable convective and radiative heat losses during operation. These losses were considered as part of the prototype-level limitations of the system. Temperature monitoring was conducted using a TM-902C digital thermometer equipped with a K-type thermocouple probe, with a measurement range of −50 to 1300 °C and a resolution of 0.1 °C. Prior to experimentation, the thermometer was calibrated using ice-water (0 °C) and boiling-water (100 °C) reference points to ensure measurement accuracy. Electrical output from the generator was measured using an analog 408 DC voltmeter (0–15 V) and a 407 DC ammeter (0–2 A), each with manufacturer-specified accuracy of ≤5% full scale. Readings were cross-checked using a digital multimeter to enhance reliability. Metal fabrication processes, including welding, drilling, and metal cutting, were carried out using standard workshop equipment to assemble and modify system components.

The turbine utilized a single-stage impulse configuration with flat plate blades fabricated from thin steel sheet. The blades were mounted radially on the rotor without airfoil curvature, resulting in a simple geometry suitable for proof-of-concept operation rather than optimized aerodynamic efficiency.

Steam was delivered to the turbine through a copper pipe (3/4 inch) with an outer diameter of 19 mm and an inner diameter of 16 mm, measuring approximately 60 cm in length. At the turbine inlet, steam entered through a single circular nozzle with an approximate inner diameter of 4–6 mm, directed toward the rotor blades. The turbine shaft was mechanically coupled to a 12 V mini DC generator using a flexible direct-drive coupling. This configuration allowed rotational power transmission while accommodating minor shaft misalignment. Fuel briquettes were formed using a cylindrical mold with a diameter of 5 cm and a height of 5 cm. The mass of briquettes and other materials was measured using digital scales to ensure consistent fuel loading during experimental trials. Overall, the system was designed as a laboratory-scale prototype to evaluate the feasibility of converting thermal energy from briquette combustion into low-level electrical output.

The experimental system was composed of mechanical, thermal, electrical, and fabrication components assembled into a laboratory-scale steam power generation prototype. The combustion process was carried out using a steel biomass stove that functioned as the combustion chamber. The stove had an internal diameter of approximately 18–20 cm and a wall thickness of about 1.0–1.5 mm. This unit served as the primary heat source for burning the briquettes and supplying thermal energy to the boiler. Steam generation was performed using a pressure cooker–type boiler made of stainless steel, with a nominal capacity of 4 L and an estimated wall thickness of approximately 2–3 mm. The boiler and its connected steam line were operated without external thermal insulation, resulting in unavoidable convective and radiative heat losses during operation. These losses were considered part of the inherent limitations of the prototype system.

Temperature was measured using a TM-902C digital thermometer equipped with a K-type thermocouple probe, covering a range of −50 to 1300 °C with a resolution of 0.1 °C. Prior to testing, the instrument was calibrated using ice-water and boiling-water reference points to ensure measurement accuracy. Electrical output from the generator was monitored using an analog 408 DC voltmeter (0–15 V) and a 407 DC ammeter (0–2 A), both with manufacturer-specified accuracy of $\leq 5\%$ full scale. To enhance reliability, readings were cross-checked using a digital multimeter. Fabrication and assembly of the prototype were conducted using standard workshop tools, including welding, drilling, and metal cutting equipment.

The turbine employed a single-stage impulse configuration. Its rotor consisted of flat plate blades fabricated from thin steel sheet and mounted radially without airfoil curvature. This simplified blade geometry was selected to enable proof-of-concept operation rather than to achieve optimal aerodynamic efficiency. Steam was delivered to the turbine through a 3/4 inch copper pipe with an outer diameter of 19 mm and an inner diameter of 16 mm, approximately 60 cm in length. At the turbine inlet, steam was directed through a single circular nozzle with an inner diameter of approximately 4–6 mm, allowing the steam jet to impinge on and pass across the rotor blades to induce rotational motion. The turbine shaft was directly connected to a 12 V mini DC generator using a flexible coupling (direct-drive configuration), enabling efficient transmission of rotational energy while accommodating minor shaft misalignment.

Fuel briquettes were produced using a cylindrical mold with a diameter of 5 cm and a height of 5 cm. The mass of briquettes and other experimental materials was measured using digital scales to ensure consistent fuel loading across trials. The materials used in this study consisted of a mixture of organic waste and plastic waste as the primary fuel source. A natural starch-based adhesive (3–5%) was added to improve briquette cohesion and structural integrity. Supporting materials included electronic components and electrical cables for power transmission and measurement, as well as copper or aluminum pipes used for steam conveyance within the system. Overall, the tools and materials were integrated into a small-scale prototype designed to evaluate the feasibility of converting thermal energy from mixed-waste briquette combustion into measurable electrical output under controlled laboratory conditions.

2.1. Safety Considerations and Emissions Limitations

Direct combustion of RDF is incomplete combustion, resulting in high CO levels, reduced flame temperatures, and the formation of pollutants [19]. The use of RDF can have environmental and economic impacts by reducing waste, thereby reducing methane emissions and soil contamination. RDF can be used as a substitute fuel for coal, reducing emissions of SO_2 and NO_x pollutants [20]. The combustion of plastic-containing RDF poses potential health and environmental risks due to the release of particulate matter and gaseous pollutants. Therefore, all experiments were conducted in a well-ventilated, open or semi-open laboratory environment, and operators used basic personal protective equipment, including heat-resistant gloves and face masks. The prototype was operated exclusively for short-duration, supervised experimental tests. This study does not claim compliance with emission standards, and no detailed flue gas analysis was performed. Accordingly, the system is explicitly presented as a controlled experimental prototype, not as a household-scale or deployable power generation device. The findings are intended to support early-stage feasibility assessment and engineering analysis, while future work should incorporate emission control measures and quantitative emission monitoring before any real-world application is considered.

2.2. *Making RDF Briquettes*

The production of RDF briquettes began with the sorting of waste materials, ensuring that the plastic content did not exceed 20%. In this study, the briquettes consisted of 80% dry organic waste and 20% plastic, corresponding to the organic fraction range specified for BBJP Class 3 in SNI 8966:2021 ($80 \leq$ organic $< 87.5\%$). The plastic fraction was intentionally fixed at 20% to represent the upper limit of the BBJP Class 3 classification, thereby enhancing the calorific value to support steam generation while maintaining combustion stability and operational safety in a laboratory-scale prototype. Lower plastic fractions were not examined in order to minimize experimental variability and maintain focus on evaluating the overall feasibility of the integrated micro-scale energy conversion system. After sorting, the waste materials were shredded or cut into smaller pieces to achieve more uniform particle size and improve mixing homogeneity. The shredded waste was then dried to reduce moisture content, ensuring more stable combustion and improved briquette quality. Subsequently, the dried material was mixed with a natural binder to enhance cohesion and structural integrity. Finally, the mixture was molded and compressed into cylindrical briquettes, producing a uniform fuel form suitable for combustion testing in the prototype system.

Preparation of Tools and Materials

Mixing

Stamping

Cooling and Drying

Figure 1. RDF Briquette Making Process

2.3. *Prototype Making of RDF-Based Power Generation Machines*

The development of the RDF-based power generation prototype was carried out through several sequential stages. First, a biomass stove was prepared to serve as the combustion unit for burning the RDF briquettes and generating thermal energy. This stove functioned as the primary heat source for the system. Next, a heating chamber was constructed to accommodate the boiler and facilitate efficient heat transfer from the combustion process to the water inside the pressure vessel. The design ensured that the generated heat was directed effectively toward steam production. A simple impulse-type micro steam turbine was then fabricated and installed. The turbine was designed as a single-stage unit to convert the kinetic energy of the steam into mechanical rotational energy. Following this, a mini DC generator was installed and mechanically coupled to the turbine shaft. Finally, electrical connections were completed, and small lights were attached as loads to demonstrate the conversion of thermal energy from RDF combustion into usable electrical energy within the prototype system. Researchers create and physically assemble components based on the designs that have been made so that they become electricity generating machines using RFD-based plastic waste

Manufacturing of propellers and turbines

Assembling it into an RDF-based power generating machine

Figure 2. RDF-based Power Generation Machine Manufacturing Process

Figure 3. RDF-based Power Generation Machine Prototype

The way this RDF-based power generating machine works is by placing RDF briquettes on a biomass stove and then burning them to produce heat that can boil water in a pressure cooker. Boiling water will produce steam so that the steam passes through a 3/4 diameter copper pipe to the turbine. The steam will drive a turbine which then drives a generator so that it becomes electrical energy that can light the lights. The electrical energy produced is measured with a voltmeter and ammeter.

2.3. How the System Works

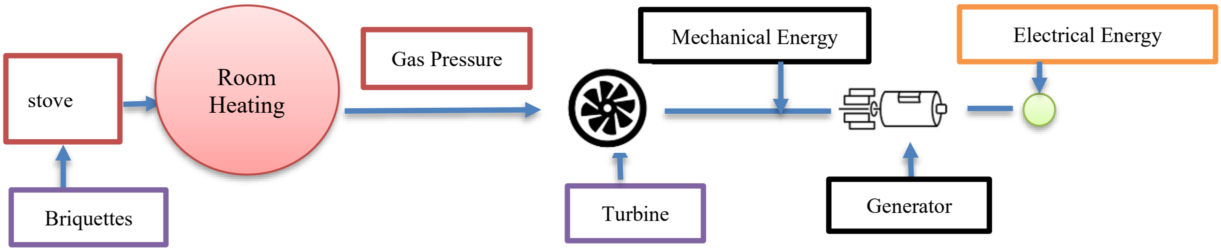

Figure 4. Device Design Schematic
Reprocessed from: Jawale et al (2022)

In this system, the energy conversion process begins in the heating chamber, where RDF briquettes are combusted to generate thermal energy. The heat produced from combustion raises the temperature of the working fluid—typically water—inside the boiler. As the temperature increases, the fluid undergoes a phase change into steam, producing pressurized gas. The buildup of gas pressure creates a high-velocity steam flow that is directed toward the turbine through a nozzle. The pressurized steam then impinges on the turbine blades, causing the rotor to spin and converting the thermal and pressure energy into mechanical rotational energy. This mechanical energy is subsequently transmitted to a generator, which converts the rotational motion into electrical energy through electromagnetic induction. The generated electricity can then be utilized to power small electrical loads.

The operation of the system begins with the combustion stage, during which RDF briquettes are burned inside the heating chamber using a biomass stove. In this stage, chemical energy stored in the fuel is released through a combustion reaction between combustible elements such as carbon (C) and hydrogen (H) and oxygen (O_2) from the air. This reaction generates heat and combustion gases, forming a flame that produces thermal energy. A simplified representation of the combustion reaction is: $C + O_2 \rightarrow CO_2 + \text{heat}$ [21]. The heat generated in this process becomes the primary energy source for the subsequent stages.

The thermal energy produced from combustion is then transferred to the boiler, where it heats the working fluid, typically water. As the temperature rises to the boiling point, the water undergoes a phase change and is converted into high-pressure steam. This stage represents the conversion of chemical energy into thermal energy and subsequently into pressure energy within the steam. In the mechanical stage, the high-pressure steam is directed through a nozzle toward the turbine blades. The force of the steam jet causes the turbine to rotate, converting the thermal and pressure energy of the steam into mechanical rotational energy. Finally, in the electricity generation stage, the rotating turbine shaft is connected to a generator. Through electromagnetic induction, the generator converts mechanical energy into electrical energy. The produced electricity can then be used to power small electrical loads, demonstrating the feasibility of the RDF-based micro-scale power generation system.

2.3. Data Processing and Analysis

Data obtained from the results of briquette testing in the laboratory will be processed using a descriptive analysis approach and an analysis of the performance of power generating machines and energy efficiency calculations will be carried out. Researchers recorded the combustion chamber temperature, pressure, electrical power output (voltage and current) periodically during the test. The results of this data processing are displayed in the form of tables and graphs to facilitate analysis.

The analysis was conducted to evaluate the thermal behavior, electrical performance, and overall energy conversion efficiency of the RDF-based power generation prototype. First, the temperature profile during combustion was analyzed to observe the pattern of thermal changes inside the combustion chamber. A thermocouple or digital thermometer was installed in the combustion zone to continuously monitor temperature. Measurements were recorded at fixed time intervals (e.g., every 1 minute) throughout the combustion process. This procedure allowed identification of ignition characteristics, peak temperature, and thermal stability during RDF briquette burning. Second, the stability of the electrical output was evaluated by measuring voltage and current generated by the system. A multimeter or datalogger was used to record voltage (V) and current (A) values over time. The average voltage and average current were calculated from the recorded data, along with their standard deviations, to assess output consistency and electrical stability during operation. The energy content of the RDF briquettes (fuel input energy) was calculated using the following equation

$$E\ \text{input} = m \times CV \qquad (1)$$

Where m represents the briquette mass (kg) and CV is the calorific value (MJ/kg). In this study, the calorific value of RDF was assumed to be 12.5 MJ/kg, which represents a commonly reported value for

Indonesian RDF based on previous studies [22,23]. The calorific value of RDF briquettes can be determined experimentally using a bomb calorimeter or estimated from literature values. Previous research reports RDF calorific values ranging from 10–25 MJ/kg, with 12.5 MJ/kg frequently adopted as a representative value for moderate-plastic-content RDF in Indonesia.

The electrical output energy generated by the system was calculated using Equation (2)

$$\mathrm{E\ electrical\ output} = \mathrm{V\ x\ I\ x\ t} \qquad (2)$$

Where V is the average voltage (volts), I is the average current (amperes), and t is the duration of electricity production (seconds). Finally, the energy conversion efficiency of the system was determined using Equation (2):

$$\mathrm{Energy\ efficiency\ (\%)} = \frac{\mathrm{E\ electrical\ output}}{\mathrm{E\ fuel\ input}} x\ 100\% \qquad (3)$$

This calculation represents the percentage of chemical energy contained in the RDF briquettes that was successfully converted into electrical energy by the prototype system.

2.4. Control Variables

The following variables were maintained constant across all experimental runs to minimize variability:

a. Water volume: kept constant in the boiler for all tests
b. Initial water temperature: maintained at ambient temperature at the start of each run
c. Ambient conditions: experiments conducted under similar environmental conditions
d. Fuel moisture: RDF briquettes prepared and air-dried under identical conditions prior to testing
e. Airflow: natural draft combustion with a fixed air inlet opening (no forced airflow)

2.5. Safety and Emission

a. Safety and Emissions Considerations
   Combustion of RDF briquettes containing plastic fractions can release potentially hazardous gaseous and particulate pollutants, including carbon monoxide (CO), volatile organic compounds (VOCs), and fine particulate matter. Therefore, safety and emissions considerations were incorporated into the experimental design.
b. Ventilation and Operator Safety
   All combustion experiments were conducted in a well-ventilated and open laboratory environment to prevent the accumulation of combustion gases. The system was operated at a safe distance, and operators were required to wear basic personal protective equipment (PPE), including heat-resistant gloves and a face shield.
c. Emission Limitation and Monitoring
   The prototype operated on a small fuel mass and short burn duration, limiting the total emissions generated during each test. Although comprehensive emission measurements (e.g., CO, NO_x, PM) are beyond the scope of this study, qualitative observations of combustion behavior (flame stability, visible smoke intensity, and odor) are warranted.
d. Scope Limitations and Justification for Application
   This system was developed strictly as a laboratory-scale proof-of-concept prototype for controlled performance evaluation of RDF-based micro-power plants. This prototype is not intended for residential or continuous operation.

3. Results and Discussion

3.1. Briquette Feasibility Analysis

The suitability of RDF briquettes can be seen from the characteristics and laboratory. In this research, RDF briquettes were measured for organic material content, diameter and thickness and tested in the laboratory in the form of water content, ash content, density and burning rate. The measurement and test results can be seen in the table below:

Table 1. Briquette Measurement and Testing Results

No	Characteristics	Mark	SNI 8966:2021
1	Organic material levels	80%	80 ≤ organic <87.5 %
2	Diameter	80 mm	50-70 mm
3	Thick	40 mm	20-70 mm
4	Water content	0.31%b/b	< 25%
5	Ash content	7.71%b/b	< 25%
6	Briquette density (density)	0.42 g/cm^3	>0.9
7	Burn Rate	0.310 g/minute	

Based on the table above, the organic material content, briquette thickness, water content and ash content are in accordance with SNI 8966:2021 which explains Solid Fuel for Power Plants. Meanwhile, the diameter and density parameters do not meet SNI 8966:2021 standards. This RDF-based power generating machine uses RDF briquettes which contain 20% plastic and 80% organic waste. This is in accordance with SNI standards [24]. According to solid fuel standards (BBJP, SNI 8966:2021), these RDF briquettes are included in the class 3 category [25].

These RDF briquettes are made in a cylindrical shape so that they are easy to make and are a common shape on the market. The adhesive used uses tapioca flour because it is a commonly found ingredient, affordable, and easy to use. Tapioca flour is used as adhesive by mixing tapioca flour with water and then heating it on the stove. When heated, tapioca flour is stirred to prevent lumps, then mixed with plastic and dry flour to make briekt. The molded briquettes are dried in the sun for 3 days [26]. The size of these RDF briquettes, 80 mm in diameter and 40 mm thick, is due to the size of the mold used. The briquette dimension deviated from the SNI reference by only about 1 cm, which may have a minor effect on combustion and heat release.

The moisture content of these briquettes meets the standard, namely 0.31%w/w (below 25%), indicating that these RDF briquettes are easy to burn without additional fuel. Low water content has an impact on the calorific value and combustion rate because the heat produced is first used to evaporate water before producing heat that can be used as combustion heat [27]. The ash content of these RDF briquettes meets the standard, namely 7.71%w/w (<25%). The ash content shows the elemental content of combustion residues with a calorific value that is no longer present or that contains only a small amount of carbon. The ash content of the briquettes will affect the combustion rate because during the combustion process, heat transfer to the inside of the briquettes and oxygen diffusion to the surface of the briquettes will be inhibited. Ash content also increases dust emissions and affects combustion volume [28]. RDF from solid waste has a higher calorific value than biomass fuels due to its higher carbon and hydrogen content, lower water content, and lower RDF ash melting temperature [19].

Briquette density shows the ratio between briquette mass and volume. The density of these RDF briquettes is 0.42 g/cm3 (<0.9), indicating that they do not meet the standards. This density does not meet the standard because the force to compact the briquettes still uses manual methods so the results are less than optimal. The briquette density value is influenced by the size and homogeneity of the charcoal as well as the amount of adhesive used. Density affects the burning rate of briquettes. The greater the density value of the briquette, the longer the burning time so that briquettes that have a low specific gravity or density will burn more easily compared to briquettes that have a high density value [28].

3.2. Performance Test Results of RDF-Based Power Plant Prototype

Tests were carried out on RDF briquettes by measuring the following parameters:

a. Combustion chamber temperature (°C)
b. Burning time (minutes)
c. Electrical voltage (volts)
d. Current strength (Ampere)
e. Electric power produced (Watts)
f. Energy conversion efficiency (%), obtained by calculating

Table 2. Test Results Based on Briquette Mass on RDF-Based Power Generation Machine Prototype

Briquette Mass (g)	**Max Temp. (°C)**	**Burning Time (minutes)**	**Electrical Voltage (V)**	**Current (A)**	**Max. Electrical Power. (watt)**	**Output Energy (J) (VxIxt)**	**Output Energy (J) (mxCV)**	**Efficiency (%)**
250	130	20	0.5	0.01	0.005	6	3.125×10^{6}	1.92×10^{-6}
500	135	20	0.7	0.02	0.014	16.8	6.25×10^{6}	2.69×10^{-6}
750	138	20	0.7	0.02	0.014	16.8	9.375×10^{6}	1.79×10^{-6}

The table above explains that based on the mass of RDF briquettes burned, the result was that the largest increase in temperature was at a mass of 500 g RDF briquettes, namely 135°C. The highest energy efficiency was obtained when using 500 g of RDF briquettes (2.69×10^{-6} %) by producing an electric voltage of 0.7 V, an electric current of 0.02 A, the electric power produced was 0.014 watts in one combustion cycle ±20 minutes.

Tests carried out to determine the relationship between heating time and steam temperature, voltage and electric current produced in 500 g briquettes can be seen in the graph below:

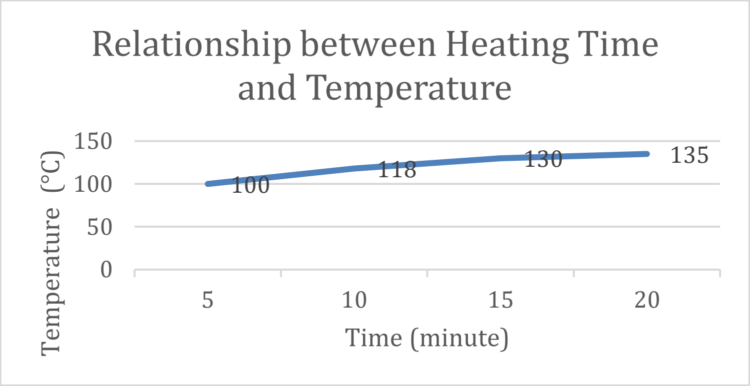

Figure 5. Graph of the Relationship between Heating Time and Temperature

Figure 5 above explains that the longer the heating time, the resulting temperature will increase to a maximum of 135 °C.

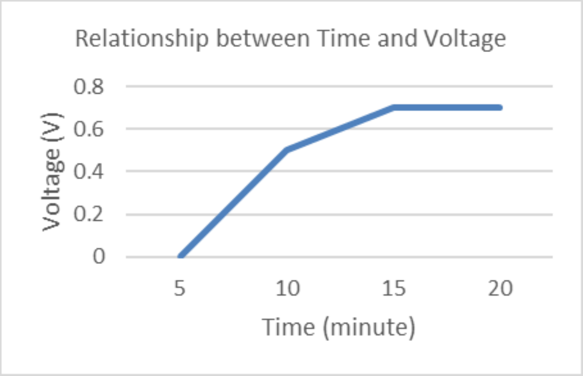

Figure 6. Graph of the Relationship between Time and the Generated Electric Voltage

Figure 6 above explains that the longer the heating time will increase the electrical voltage produced but then it becomes stable at a voltage of 0.7 volts.

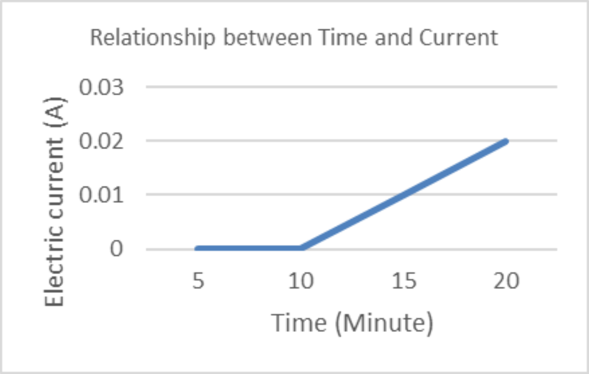

Figure 7. Graph of the Relationship between Heating Time and the Electric Current Generated

Figure 7 above explains that the longer the heating time will increase the electric current to 0.02 A in 20 minutes.

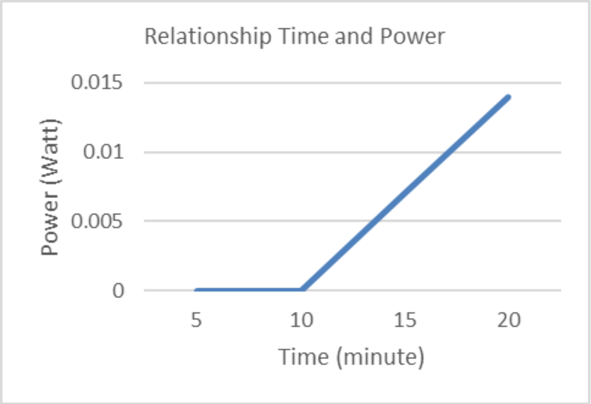

Figure 8. Graph of the Relationship between Heating Time and the Electrical Power

Figure 8 above explains that the longer the heating time will increase the electrical power produced to 0.014 Watts.

3.3. Discussion and Analysis of Machine Based Power Generating Machine Making RDF

In the design of this RDF-based power plant prototype, the pipe used to transmit hot steam is a ¾ size copper pipe. Small size pipes are used because a small pipe diameter will produce greater gas pressure, resulting in greater electrical energy. The increased energy is due to the increasing kinetic energy produced by the gas. Researchers use a DC motor dynamo because it is simple compared to AC motors which require a more complex inverter and controller. DC motors are often used in portable applications such as electric vehicles, handheld power tools, and robotics because they can directly use battery (DC) power sources, which do not require conversion from AC to DC.

Researchers use a pressure cooker because it replaces the function of a compressor which can add pressure to the steam/gas produced from heating plastic. The pressure cooker has a safety valve that can be opened to control the pressure. The turbine used uses iron because it does not melt easily and spins easily. This research uses an impulse type steam turbine. The flow of steam through the nozzle and moving turbine blades works on the principle of impulse, namely the conversion of pressure into motion in the nozzle. Force and torque on the rotor occur due to changes in directional momentum and steam pressure as it passes through the turbine blades [29].

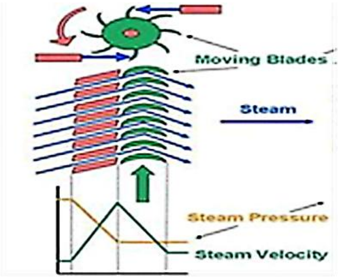

Figure 9. Desain Turbin Impuls
Source: Rathore et al. [29].

The image above explains the decrease in flow velocity and steam pressure. It can be seen in the picture that there is a flow line that bends when the steam hits the turbine. The steam flow speed decreases because the turbine rotor absorbs some of the kinetic energy of the steam which causes the rotor to rotate. Rotation of the rotor results in a change in steam velocity in the tangential direction which consequently reduces the total amount of energy that can be extracted from the steam [30].

3.4. Discussion and Analysis of Performance Test Results of Power Generation Machines based on RDF

When plastic-containing RDF briquettes are combusted in the biomass stove, the released thermal energy is transferred to the pressure cooker–type boiler, where it heats the water and converts it into steam. In this system, a sequence of energy transformations occurs. Initially, chemical energy stored in the RDF is converted into heat energy through the combustion reaction. The heat generated from burning the RDF is conducted through the boiler walls and absorbed by the water inside. As the water temperature increases, it undergoes a phase change into steam. The high-temperature steam possesses kinetic energy, which is directed through the nozzle toward the turbine blades. The force of the steam jet causes the turbine rotor to rotate, thereby converting the thermal and kinetic energy of the steam into mechanical energy. The mechanical energy generated by the rotating turbine shaft is then transmitted directly to the generator shaft through a coupling mechanism. The generator (dynamo) converts this mechanical energy into electrical energy through electromagnetic induction. The resulting electrical output can subsequently be used to power small electronic devices, such as lighting systems, within the limitations of the prototype's performance [31].

Effect of Briquette Mass on Temperature and Pressure The increase in RDF briquette mass is directly proportional to the resulting temperature and pressure. This is caused by the greater heat energy content. The more plastic waste that is burned, the more gas vapor is produced so that the rotating force is greater and the turbine rotates faster, thus producing greater electrical energy [32]. From the test results, it was found that the greater the mass of the briquettes, the greater the electrical power produced. The larger mass of RDF briquettes will allow the steam temperature and pressure to reach optimal values more quickly and last longer, so that the turbine rotation is more stable and produces more electrical power. From the data it can be seen that the increase in steam temperature from 100 °C to 135 °C is directly proportional to the increase in output voltage from 0 V to 0.7 V. The voltage begins to stabilize in the 15th minute at a temperature of 130 °C, indicating that the system requires a warm-up time before reaching optimal performance. This stability occurs because the system has reached a saturation condition, where the pressure and temperature are relatively constant so that the turbine rotation and generator output no longer fluctuate greatly.

From the test results it was found that the highest conversion efficiency was obtained when using 500g RDF briquettes ($2.69 \text{ x}10^{-6}\%$). The efficiency value of the RDF generator is very small due to the turbine and propeller being made from used cans with a simple design, the use of a pressure cooker which has not optimal pressure and there is still a lot of leakage from the steam produced into the air. Although increasing the briquette mass from 500 g to 750 g slightly increases the maximum temperature, the electrical output does not increase proportionally. This may be due to the system possibly reaching a thermal-mechanical saturation threshold, where additional combustion energy is not effectively converted into usable steam enthalpy at the turbine inlet. The boiler's heat transfer surface area may limit the absorption of additional energy beyond a certain combustion intensity, causing excess heat to be dissipated to the surrounding environment rather than contributing to steam production. A higher briquette mass may reduce the oxygen availability in the fixed combustion chamber, leading to incomplete combustion and reducing effective heat utilization. Steam leaks in a poorly sealed system may limit the turbine inlet pressure. The turbine/nozzle geometry may be optimized for a specific mass flow rate; exceeding this range may reduce expansion efficiency.

Based on test results, this prototype is capable of producing an electric current of 0.02 A, a voltage of 0.7 V and a power of 0.014 Watt from 500 g of RDF briquettes in one combustion cycle of ±20 minutes. Microscale steam turbine system on the Spirax Sarco TurboPower prototype [33] producing 50 kW per unit. Commercial and industrial micro gas turbines typically operate in the 30–350 kW range with thermal efficiencies between 26% and 31% [34]. Low efficiency indicates performance losses in heat transfer, steam quality, and mechanical coupling. This prototype is positioned as an early-stage feasibility demonstration, not yet capable of being used as a functional power generation device. To improve the prototype's performance, several engineering improvements are required. First, the steam circuit must be converted to a closed, leak-tight system with verified fittings and a calibrated pressure gauge, supported by pressure control to maintain stable operating conditions. Second, heat losses must be reduced through high-temperature insulation of the combustion chamber and boiler, improved flame-boiler coupling, and increased heat transfer surface area to increase achievable steam temperatures and pressures. Third, the nozzle size and turbine design must be appropriate for the achievable pressure-to-mass flow ratio, along with low-friction bearings to improve mechanical efficiency and rotational speed. Finally, a generator with the turbine's speed-torque characteristics should be selected and basic power electronics and buffers (rectifiers and small storage) integrated to stabilize usable output. This study used only one test per condition, so the results are preliminary. Future research should incorporate repeated trials.

The main limitations of this study lie in the limited range of briquette masses and firing durations, as well as incomplete control of operational variables (water volume, initial temperature, ambient conditions, fuel humidity, and airflow). The very low efficiencies observed reflect prototype-level limitations, including low steam pressure, significant heat losses, unoptimized turbine geometry, and the use of a low-power DC generator. Consequently, these results should be interpreted as an indication of functional feasibility and system integration, rather than as a representation of scalable or commercially viable performance. The findings of this study should be interpreted as preliminary, proof-of-concept results, and further research is needed with a wider mass range, varying firing durations, thermal management, pressure control, different plastic fractions and energy conversion efficiency.

4. **Conclusion**

This study successfully designed and tested a laboratory-scale prototype for converting Refuse-Derived Fuel (RDF) into electrical energy. RDF briquettes composed of 80% dry organic waste and 20% plastic were produced and met relevant SNI standards for material composition, ash content, moisture content, and combustion characteristics. The best performance was obtained using 500 g of RDF briquettes, generating a maximum voltage of 0.7 V, a current of 0.02 A, a combustion temperature of 138 °C, and an energy conversion efficiency of 2.69×10^{-6}%. Although the efficiency remains very low due to non-optimized turbine geometry, limited boiler pressure, and steam leakage, the results demonstrate proof-of-concept feasibility of RDF-to-electricity conversion. Further subsystem optimization, improved sealing and pressure control, and emission validation are necessary before practical or real-world implementation can be considered. Further development of this prototype should focus on improving both environmental safety and system performance. The integration of a gas cleaning or steam filtration system is recommended to reduce odors and potentially hazardous compounds generated from plastic combustion. In addition, optimization of turbine geometry and generator matching is necessary to enhance energy conversion efficiency and increase electrical output. Future studies should also consider incorporating an energy storage system, such as a battery, to enable more stable and sustainable electricity supply beyond immediate real-time generation.

Declaration of AI and AI assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to an assistive tool to support language refinement and improve the clarity of writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Wirasasmita RH, Arianti BDD, Uska MZ, Kholisho YN, Wardi Z, Gunadi RAA, et al. Bahaya Sampah Plastik bagi Kesehatan dan Lingkungan. ABSYARA: Jurnal Pengabdian Pada Masyarakat 2020;1:1–8. https://doi.org/10.29408/ab.v1i2.2749.

[2] Zulhusni M, Sari CA, Rachmawanto EH. Implementation of DenseNet121 Architecture for Waste Type Classification. Advance Sustainable Science, Engineering and Technology 2024;6:1–9. https://doi.org/10.26877/asset.v6i3.673.

[3] Nadeem. Green Careers Guide. British Council n.d. www.britishcouncil.org/climate-connection (accessed September 7, 2024).

[4] Rawool A, Rane D, Holkar K, Sawardekar T, Khan F. Utilization of Waste Plastic to Electricity Using Pyrolysis Process. International Research Journal of Engineering and Technology 2019;6:1248.

[5] Nayanathara Thathsarani Pilapitiya PGC, Ratnayake AS. The world of plastic waste: A review. Cleaner Materials 2024;11:100220. https://doi.org/10.1016/j.clema.2024.100220.

[6] Widiyatmoko H, Purwaningrum P, Putri Arum P F. Analisis Karakteristik Sampah Plastik Di Permukiman Kecamatan Tebet Dan Alternatif Pengolahannya. Indonesian Journal of Urban and Environmental Technology 2016;7:24–31. https://doi.org/10.25105/urbanenvirotech.v7i1.713.

[7] Pujari P, Sutar F, Jagadale S, Kabara R, Sawan V. Make Electricity by Plastic and Waste Materials. International Journal of Research Publication and Reviews 2022;3.

[8] Purwaningrum P. Upaya Mengurangi Timbulan Sampah Plastik Di Lingkungan. Indonesian Journal of Urban and Environmental Technology 2016;8:141–7. https://doi.org/10.25105/urbanenvirotech.v8i2.1421.

[9] Siregar SH, Mubarak, Zulkifli. The Impact of Plastic Waste Pollution on Mangrove Ecosystems in Pangkalan Sesai Village, Dumai City Sofyan. Journal of Rural and Urban Community Empowerment 2023;4:84–90.

[10] Olofsson F, Halvarsson H. Small scale energy conversion of plastic waste: Identification of gasification process parameters through modelling in Aspen Plus 2020.

[11] Alham NR, Utomo RM, Larasati TD, Muslimin, Kurniawan A, Yusril RSM, et al. Designing a Waste Power Plant (PLTSA) Prototype Based on the Type of Waste as a Renewable Energy Source. Atlantis Press International BV; 2023. https://doi.org/10.2991/978-94-6463-180-7_11.

[12] Statistik P. Statistik pln. Statistik PLN 2022:98.

[13] Lale S, Patade O, Bhagat K, Dalavi S. Generate electricity by Using Waste Garbage 2024:797–9.

[14] Sharanya D, Babu AV, Sunay K, Charan BKC, Abhilash K. Electricity Generated by Waste Material. International Research Journal of Engineering and Technology 2022;9:1651.

[15] Purwanto H, Nurhasana R, Rohimah A. Assessing the Feasibility of Small-Scale RDF Technology in Urban Solid Waste Management Using Cost-Benefit Analysis. Advance Sustainable Science, Engineering and Technology 2025;7:1–15. https://doi.org/10.26877/asset.v7i3.1988.

[16] Salaripoor H, Yousefi H, Abdoos M. Life cycle environmental assessment of Refuse-Derived Fuel (RDF) as an alternative to fossil fuels in cement production : A sustainable approach for mitigating carbon emissions. Fuel Communications 2025;22:100135. https://doi.org/10.1016/j.jfueco.2025.100135.

[17] Fauziah EN, Sari MM, Suryawan IWK. Possibility of Municipal Waste Management with Refuse-Derived Fuel (RDF) Mixed Paper and Garden in Depok City. Indonesian Journal of Applied Environmental Studies 2023;4:33–8. https://doi.org/10.33751/injast.v4i1.7171.

[18] Muhammad G. Ubah Sampah Kota Jadi Bahan Bakar PLTU, PLN dan Pemkot Medan Bangun Pabrik Biomassa. PT PLN 2022. https://web.pln.co.id/media/siaran-pers/2022/12/ubah-sampah-kota-jadi-bahan-bakar-pltu-pln-dan-pemkot-medan-bangun-pabrik-biomassa?utm_source=chatgpt.com (accessed April 25, 2025).

[19] Bui VG, Vo AV, Ngoc T, Ho A, Do PN. Simulation and Experiment Study of Refuse Derived Fuel (RDF) Combustion in Atmospheric Conditions 2026;20:229–36.

[20] Sharma U, Sharma D, Kumar A, Bansal T. Utilization of refuse-derived fuel in industrial applications : Insights from Uttar Pradesh , India. Heliyon 2025;11:e41336. https://doi.org/10.1016/j.heliyon.2024.e41336.

[21] Batubara B, Jamilatun S. Sifat-Sifat Penyalaan dan Pembakaran Briket Biomassa, Briket Batubara dan Arang Kayu. Sifat-Sifat Penyalaan Dan Pembakaran Briket Biomassa, Briket Batubara Dan Arang Kayu 2012;2:37–40. https://doi.org/10.22146/jrekpros.554.

[22] Paramita W, Hartono DM, Soesilo TEB. Sustainability of Refuse Derived Fuel Potential from Municipal Solid Waste for Cement's Alternative Fuel in Indonesia (A Case at Jeruklegi Landfill, in Cilacap). IOP Conference Series: Earth and Environmental Science 2018;159. https://doi.org/10.1088/1755-1315/159/1/012027.

[23] Tihin GL, Mo KH, Onn CC, Ong HC, Taufiq-Yap YH, Lee HV. Overview of municipal solid wastes-derived refuse-derived fuels for cement co-processing. Alexandria Engineering Journal 2023;84:153–74. https://doi.org/10.1016/j.aej.2023.10.043.

[24] Nasional BS. SNI 8966: 2021 Bahan Bakar Jumputan Padat 2021.

[25] Maulidayanti EM, Yuliani M, Robbani MH, Wiharja W, Hambali E, Setyaningsih D. Evaluating Refuse-Derived Fuel (RDF) Production fromMunicipal Solid Waste (Case Study: Cilacap Regency RDF Plant). Jurnal Teknologi Lingkungan 2024;25:179–89. https://doi.org/10.55981/jtl.2024.1008.

[26] Pratiwi VD, Mukhaimin I. The Influence of Temperature and Types of Adhesive on Biobriquettes from Coffee Pulp with Torrefaction Method. CHEESA: Chemical Engineering Research Articles 2021;4:39. https://doi.org/10.25273/cheesa.v4i1.7697.39-50.

[27] Dewi R, Hasfita F. Pemanfaatan Limbah Kulit Jengkol (Pithecellobium jiringa) menjadi Bioarang dengan Menggunakan Perekat Campuran Getah Sukun dan Tepung Tapioka. Jurnal Teknologi Kimia Unimal 2016;5:105. https://doi.org/10.29103/jtku.v5i1.83.

[28] Rozidi, Sukmawati, Setiawat DA, Fuadi M. Analysis of The Quality of Sawdust Briquettes With Adhesive Banana Starch Flour (Musa paradisiaca L.). J-AGENT 2024;2:88.

[29] Rathore P, Sen PK, Sahu G, Sharma R, Bohidar S. A Review on Steam Turbine Blade Desingand It's Principle. International Journal of Science Technology & Engineering 2015;2:4–8.

[30] Salmali. Wind Turbin Momentum Theory 2022. https://www.mechnflow.com/post/wind-turbine-momentum-theory#google_vignette (accessed September 7, 2024).

[31] Yani A, Mustafa D, Taqwa T. Rancang Bangun Prototype Pembangkit Listrik Tenaga Uap Mini Sebagai Media Praktikum Mahasiswa. Turbo : Jurnal Program Studi Teknik Mesin 2018;7:43–7. https://doi.org/10.24127/trb.v7i1.711.

[32] Apsara HK, Vinutha C, Motebennuru V, Yeshash SP. Generation of Electricity by Plastic Waste 2023;6:4–10.

[33] Alford A, Nichol P, Frisby B. The Development of a Small High Speed Steam Microturbine Generator System The Development of a Small High Speed Steam Microturbine Generator System. IOP Conf Series: Materials Science and Engineering 2015;90. https://doi.org/10.1088/1757-899X/90/1/012062.

[34] Tursucular ED, Kagaroz I. Micro Turbines : A Literature Mini-Review. EU 4th International Conference on Health, Engineering And Applied Sciences 2024:318–28.