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Design Of A Waste-Free Power Plant Using A Thermoelectric Generator As A Supply Source For Lamps

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Abstract

Waste management poses a significant environmental challenge in Indonesia. Ineffective waste handling can lead to various negative environmental impacts. Meanwhile, energy demand continues to rise in line with population growth. One innovative solution to address these issues is the use of Thermoelectric Generator (TEG) technology in a Waste-to-Energy Power Plant (PLTSa) system. This study aims to design and develop a power generation system that utilizes heat energy from the combustion of waste—specifically plastic and paper—to generate electricity, which is then used as a power source for lighting systems. This research uses a quantitative descriptive method to explain a phenomenon or process without relating it to other variables. The energy conversion process is carried out using six TEG modules connected in series to maximize voltage output. The generated voltage is then regulated and stored in a battery using a Solar Charge Controller (SCC), and monitored through an INA219 sensor and an Arduino UNO microcontroller. The system is also equipped with a photocell sensor that enables the light to operate automatically based on the ambient light intensity. Test results show that a temperature difference (ΔT) of 227.7°C between the hot and cold sides of the TEG can produce a maximum voltage of 15.87 Volts. The monitoring and automatic control system functions effectively in tracking the TEG output and switching the light on or off according to environmental lighting conditions. Therefore, this system presents a viable alternative solution for renewable energy generation based on waste management.
Keywords : *Waste-to-energy power plant, Thermoelectric Generator, renewable energy, photocell.*

INTRODUCTION

With the rapid development of technology and industry, the waste problem is increasingly becoming a global concern. In Indonesia, waste management has become a pressing issue due to population growth and the ongoing urbanization process. Waste is any material that is no longer usable or valuable to an individual or society. Waste originates from various human activities, including household, commercial, industrial, and institutional activities. In the environment, waste can be divided into two main categories: organic waste and inorganic waste. Organic waste includes materials that can decompose naturally, such as food scraps, leaves, paper, and agricultural waste. Organic waste is biodegradable, meaning it can be broken down into simpler components with the help of microorganisms in a relatively short time. Meanwhile, inorganic waste consists of materials that are difficult to decompose and take a very long time to decompose, such as plastic, glass, metal, and other synthetic materials (Julia Lingga, Yuana, Aulia Sari, Nur Syahida, & Sitorus, 2024).

Plastic waste is the most difficult type of waste to fully decompose in the environment, while paper waste is often discarded without proper recycling. Ineffective waste management can have various negative impacts on the environment. Furthermore, a lack of public awareness and participation in waste management is also a significant challenge. Amidst these challenges, energy demand is increasing along with population growth. Therefore, more efficient and innovative waste management and the utilization of renewable energy sources are crucial (Toif Fadzoli, Rahayu Subekti, & Waluyo Waluyo, 2023).

Waste-to-Energy Power Plants (WPPs) are an innovative solution that can utilize waste as an energy source. By converting waste into electricity, WPPs not only help reduce waste volume but also provide an environmentally friendly energy alternative.

One technology that can be applied to waste-to-energy plants (PLTSa) is *the Thermoelectric Generator* (TEG), which converts temperature differences into electrical energy. This technology can be used to generate electricity, which is then used to power lamps.

Previous research by Hidayati (2024) conducted research on the design of public street lighting based on a waste-to-energy power plant that uses four kilograms of inorganic waste burned for five minutes to produce a voltage of fourteen *volts* . The study used five TEGs capable of producing a DC voltage of one to fifteen *volts* . With a twelve- *volt battery specification* , this system can power a lamp with a specification of thirteen *watts* for two hours. Then Agung (2020) also conducted a similar study using TEGs. As a power source in a toaster using three TEGs, it can produce a voltage of eight *volts* at a temperature difference of sixty-two degrees Celsius. The greater the temperature difference in the TEGs, the greater the voltage produced (C. I. C. Suwarno & Sukarwoto, 2024).

Based on this background, the author will raise a Final Project entitled **"Design and Construction of a Waste-to-Energy Power Plant Using *a Thermoelectric Generator* as a *Supply Source* for Lamps".** Thus, This research is expected to provide a positive contribution to waste management and the use of renewable energy.

Design

Design and construction is a systematic process that aims to produce a system, product, or technical solution through design and construction stages based on predetermined needs. In the context of engineering and technology, design and construction is not only limited to the *visual design aspect* , but also includes testing, evaluation, and integration of complex system functions. Design and construction is an integrated method that combines design and implementation processes simultaneously to increase efficiency and effectiveness in producing products or systems that meet user needs. This approach is very important in multidisciplinary projects because it is able to minimize discrepancies between the final results and the initial requirements (Mulyanto, Hamdani, & Hasmawati, 2020).

The design and development process generally involves problem identification, needs analysis, initial design, implementation, testing, and evaluation. These stages are interconnected and must be carried out iteratively to ensure the resulting solution is truly optimal and can be used according to its function. In practice, the design and development approach is widely used in various fields such as information technology development, software engineering, learning systems, and electronic devices. The design and development process must involve user participation from the initial stage to ensure the system developed truly addresses real-world problems. Thus, the design and development concept requires a deep understanding of the problem at hand and careful planning to ensure the development process is systematic and measurable (Adeleri & Rahmi, 2024).

Waste-to-Energy Power Plant (PLTSa)

Due to its biodegradable nature, organic waste can be broken down into simpler components with the help of microorganisms relatively quickly. In contrast, inorganic waste consists of materials that are difficult to decompose and take a very long time to degrade, such as plastic, glass, metal, and other synthetic materials (Julia Lingga et al., 2024).
Electricity generation can be achieved through two methods: incineration *and* gasification. Incineration *is* a process in which waste is burned at high temperatures to generate heat, which is then used to heat water and produce steam that drives a turbine to generate electricity (Cahyadi & Napitupulu, 2024). Gasification, on the other hand, is the process of converting waste into synthetic gas (*syngas*) through heating under oxygen-limited conditions. The resulting *syngas* can be used as fuel for electric generators or further processed into liquid fuel (Utoyo & Sudarti, 2022).

***Thermoelectric Generator* (TEG)**

A thermoelectric generator (TEG) is a device that generates electricity by utilizing the conductivity or heat transfer capacity of metals. A TEG converts temperature differences into electrical energy through a principle known as the *Seebeck effect* . The *Seebeck effect* works by generating an electrical voltage when two connected materials or metal plates are at different temperatures. Each material has a different *Seebeck coefficient, and the higher the Seebeck coefficient* , the greater the potential difference produced. (Almunir, 2023).

Battery

A battery or accumulator is an electric cell that undergoes a reversible electrochemical process *with* a high degree of efficiency. This reversible electrochemical process allows chemical energy to be converted into electrical energy during discharge, and conversely, electrical energy can be converted back into chemical energy during recharging, through electrode regeneration by passing an electric current in the opposite direction (reversepolarity) within the cell (Nurjanah, Miftahul Huda, Saputra, Sahara, & Hasanudin, 2021).
The working principle of a battery is based on chemical reactions that occur within an electrochemical cell. Each cell has two electrodes, an anode (negative) and a cathode (positive), contained within an electrolyte. When the battery is used, a redox (reduction-oxidation) reaction occurs between the electrodes, resulting in a flow of electrons from the anode to the cathode through an external circuit, producing an electric current. This process also involves the movement of ions within the electrolyte to maintain charge balance (Nasution, 2021).

Relay Module

The working principle of a relay is based on electromagnetism. When an electric current flows through the relay *coil* (electromagnetic coil), the *coil* produces a magnetic field that attracts the spring-loaded *armature* (support). The movement *of the armature* causes the relay switch to switch from the *Normally Open* (NO) position to closed, or from *the Normally Closed*

(NC) position to open. When the current in the coil is stopped, the magnetic field will disappear, *the armature* will return to its original position, and the switch will return to its initial state (Arba'i Yusuf, Asni Tafrikhatin, Jati Sumarah, & Hudaifah, 2023) .

A relay has three *input pins* , each of which functions to control the relay. These pins are GND, VCC, and IN. GND serves as *ground* or 0 V, VCC for a positive 5 V voltage, and IN is the input pin used to activate the relay sensor. Relay modules are used in many home automation system applications, such as controlling lights, fans, and pumps (Adeleri & Rahmi, 2024) .

A photocell sensor is an electronic component containing an LDR (*Light Dependent Resistor*) and functions based on the intensity of the light it receives. Photocells act as a replacement for manual switches with automatic switches. (Ramadhan, Amin Ash Shabah, & Rahmawati, 2024). Photocell sensors can also be used to control electronic devices, such as automatic curtains that open or close based on light intensity (Faroh, Bachri, Irawan, Nisa, & Mahendra, 2023).

LED (*Light Emitting Diode*) lamps are a type of lamp that uses light-emitting diodes to produce light with high efficiency and low power consumption. DC LED lamps function with direct current (DC) and are widely used in various applications, from household lighting to industrial and outdoor lighting (S. Suwarno et al., 2025). One of the main advantages of LED lamps is their excellent efficiency, because these lamps are able to produce more light (lumen) per *watt* compared to incandescent or fluorescent lamps. LED lamps have a longer lifespan, reaching 25,000 to 50,000 hours, which reduces the frequency of replacement and maintenance costs (Handari, 2020).

DC LED lights also have environmental benefits, as they do not contain hazardous materials like mercury, which is commonly found in fluorescent lamps. Furthermore, DC LED lights can operate at low voltages, making them safer for use in a variety of applications, including solar power systems. In use, DC LED lights typically require an LED driver to regulate the incoming current and voltage, ensuring efficient operation and resistance to damage from power fluctuations (Suprihardi, Yaman, 2020).

LCD (*Liquid Crystal Display*) is a type of electronic display that utilizes CMOS technology, which operates by reflecting light from the front or transmitting light from the back. LCD consists of a layer of organic material placed between transparent glass with indium oxide electrodes, and a layer of electrodes on the back of the glass. The main function of LCD is to display information in the form of characters, letters, numbers, or graphics (Krsimantoro, Soetedjo, & Limpraptono, 2023) .

The INA219 sensor is a module used to measure current and voltage, designed for power monitoring applications in electronic systems. This sensor is designed to measure current and voltage, specifically for power monitoring applications in electronic systems. Using differential measurement technology, this sensor can measure current, voltage, and power accurately, and is capable of measuring currents up to 3.2 *amperes* and voltages up to 26 *volts* . The INA219 communicates with a microcontroller via an I2C interface, allowing multiple devices to be connected in a single communication path, thus facilitating integration in Arduino or Raspberry Pi-based projects. This sensor is very useful in applications such as battery monitoring, power management, and measuring the efficiency of solar power systems (Dwika, Sihaloho, & Rahmadewi, 2024).

The INA219 sensor is equipped with several ports and pins that support its functionality. The main port is the I2C pin, which consists of the SDA (Serial Data Line) and SCL (Serial Clock Line) pins for data communication. In addition, there is a VCC pin used to provide power to the sensor, and a GND pin that functions as a ground. This sensor also has VIN+ and VIN- pins used to connect the voltage source to be measured, as well as an OUT pin that can be used to connect a load (Wicaksani & Nurpulaela, 2023).

The LM2596 Step-Down Module is a *switching module* that reduces a higher *input voltage to a* lower *output voltage. This component is widely used in various electronic applications due to its high power conversion efficiency and ease of use. This module is a DC converter* used to lower DC voltage, such as from 12 *volts* to 5 *volts* or from 24 *volts* to 12 *volts.* (Setiawan et al., 2022).

The LM2596 *Step Down Module* has two types: an *adjustable version with* adjustable *output* voltage , and a *fixed voltage version* with a fixed *output voltage* . This module is typically equipped with overcurrent, overvoltage, and overtemperature protection. This module enhances safety during use, and is more efficient and reliable in its implementation (Akbar Septiyoko, Indrianto Sudjoko, Iswahyudi, Penerbangan Surabaya, & Jemur Andayani No, 2022) .

The Arduino IDE (*Integrated Development Environment*) is software used to write, edit, and upload programs to the Arduino microcontroller board. The Arduino IDE supports the C/C++ programming language, which has been customized to simplify hardware programming. One of the Arduino IDE's main features is its ability to provide various libraries *that* allow users to easily access and control various sensors, actuators, and other modules (Karami et al., 2021) .

The Arduino IDE has key features such as a *verify button* to check for errors in the code, an upload button to upload the program to the microcontroller, and options for setting *the board* and *port* used. The use of the Arduino IDE is crucial in developing Arduino-based applications because it simplifies the programming process, from writing code, checking for errors, to uploading the program to *the hardware* . Before uploading the program, the user must configure *the board* and *port* according to the device being used (Kamal, Tyas, Buckhari, & Pattasang, 2023).

RESEARCH METHODS

This research uses a quantitative descriptive method. This method aims to describe the object under study based on data or measurement results. According to Sugiyono (2020), descriptive methods are used to explain a phenomenon or process without linking it to other variables or testing a specific hypothesis. This method is expected to provide a clear understanding of the performance of waste-to-energy power plants using Thermoelectric Generators (TEGs) as a power source for lamps. The stages in the quantitative descriptive method consist of (Sendrós, Himi, Lovera, Rivero, Garcia-Artigas, et al., 2020):

a. Problem Identification

The research process begins with identifying the problem to be solved: the need to manage waste while simultaneously providing a renewable energy source. In the context of this research, the identified problem is how to utilize waste as an energy source using a Thermoelectric Generator (TEG).

b. Tool Design

Once the problem is identified, the next step is to design a waste-to-energy power generation system using TEG. This includes selecting components such as TEG, SCC, INA219 sensor, battery, Arduino UNO, DC LED light, photocell sensor, relay, and LM2596 step-down module, then assembling them according to the design (Sendrós, Himi, Lovera, Rivero, Garcia-Artigas, et al., 2020).

c. Tool Testing

Once the device is complete, testing is performed to ensure its performance as designed. Several parameters are tested to ensure each component is functioning.
d. Data Analysis
The collected data was then analyzed to evaluate the overall performance of the device. The data analysis technique used was to measure the voltage obtained from the TEG based on the temperature difference (Alarifi, Abdelrahman, & Hazaea, 2022).
Calculating the percentage error between the INA219 sensor measurements and a digital multimeter. Additionally, an analysis of battery charging duration and lamp on time was performed (Suyitno, Anitasari, Rakha, Kamin, & Nurtanto, 2022).

RESULTS AND DISCUSSION

Research result

This research resulted in a waste-to-energy power generation system based on a Thermoelectric Generator (TEG) that functions as a power source for an automatic lighting system using DC lamps. This system consists of several main components that are integrated with each other, including the TEG, INA219 sensor, SCC, battery as energy storage, LM2596 step-down, Arduino Uno, photocell sensor, relay, and DC lamp as the final load.

Hardware Manufacturing

Designing a TEG requires a thorough understanding of its characteristics for the system to function efficiently. TEGs operate on the basis of the Seebeck effect. The Seebeck effect generates a voltage difference when there is a temperature difference between two different materials. TEGs consist of thermoelectric materials such as bismuth telluride (Bi_2Te_3) for low temperatures and lead telluride (PbTe) for higher temperatures, which have high Seebeck coefficients and low thermal conductivity, enabling them to efficiently convert heat into electrical energy. The Seebeck coefficient indicates how much voltage difference can be generated from a temperature difference. Materials with higher Seebeck coefficients are more efficient at generating voltage from a temperature difference (Almunir, 2023).
To maximize energy output, TEGs can be connected in series. By connecting six TEGs in series, the positive end of the first TEG is connected to the negative end of the second TEG, and so on. The total output is taken from the positive end of the first TEG and the negative end of the last TEG. This way, the electrical energy generated from the heat of waste combustion can be maximized to charge batteries and power loads (lights).

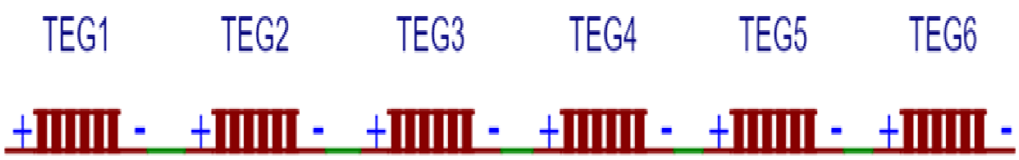

Figure 1. TEG circuit

This research discussion outlines how a TEG-based waste-to-energy power generation system can function according to its design objectives and specifications. Each aspect is thoroughly tested and analyzed to evaluate energy conversion effectiveness, sensor accuracy, power supply stability, and the responsiveness of the automatic control system (Omran & Fabritius, 2017).

Test Results

a. TEG testing

The TEG test aims to determine the TEG module's ability to convert heat energy from waste combustion into electrical energy. The main parameters observed in this test are the temperature difference between the hot and cold sides (ΔT) and the voltage generated from the waste combustion process. In this study, the TEG testing stages were as follows:

1) Prepare 6 TEG modules that have been arranged in series.
2) Place the TEG on top of the waste burning chamber.
3) Make sure the cold side of the TEG is cooled (50 ml of water in each TEG) to create the maximum temperature difference between the hot side and the cold side.
4) Connect the TEG to the SCC and INA 219 to charge the battery and measure the voltage displayed on the LCD.
5) Burn paper and plastic waste.
6) Record the temperature of the hot side and cold side using an infrared thermometer.
7) Note any voltage changes that occur.

Table 1. TEG Measurement Data

Hot Temperature (°C)	Cold Temperature (°C)	ΔT (°C)	Voltage (V)
159.3 (°C)	56 (°C)	103.3 (°C)	9.03 V
178.5 (°C)	45.1 (°C)	133.4 (°C)	10.98 V
205.9 (°C)	39.3 (°C)	166.6 (°C)	12.79 V
240.7 (°C)	33.8 (°C)	206.9 (°C)	14.45 V
252.9 (°C)	25.2 (°C)	227.7 (°C)	15.87 V

Figure 2. TEG testing

From the TEG test above, it can be seen that the temperature difference from 166.6 to 227.7 degrees Celsius will produce a voltage of 12 to 15 Volts, which means it can charge a 12 Volt 5 Ah battery. However, when the temperature on the cold side of the TEG increases, which is above 45 degrees Celsius and when the temperature on the hot side of the TEG decreases, which is less than 178.5 degrees Celsius, the ΔT difference decreases so that the voltage produced by the TEG decreases, which is 10.98 Volts, meaning the TEG cannot charge the battery. The increase in temperature on the cold side of the TEG occurs because the heat from the hot side of the waste combustion is channeled through the TEG material to the cold side through the conduction process, therefore it is necessary to add ice crystals periodically until the temperature on the cold side of the TEG is less than 40°C to keep the temperature of the cold side low. If the cold side of the TEG is not given water and ice, it will potentially accelerate the decline in the performance of the TEG module and cause permanent damage to the TEG because the material used in the TEG is bismuth telluride which is very sensitive to temperature (de Bercegol & Monstadt, 2018). Meanwhile, the decrease in temperature on the hot side of the TEG is caused by the reduction in waste combustion in the combustion chamber, so that the resulting heat temperature also decreases. Based on the test results, it can be concluded that the voltage output produced by the TEG is greatly influenced by the large temperature difference between the two sides of the TEG surface. The greater the ΔT created by the increase in temperature on the hot and cold sides of the TEG, the greater the voltage produced. This is in accordance with the principle of the Seebeck effect, which states that an electrical potential difference will appear when there is a temperature gradient between two points on a conductor material.

b. Monitoring System Testing

The monitoring system in the waste-to-energy power plant monitors the voltage generated by the TEG in real time. The main component of this system is the INA219 sensor connected to an Arduino Uno microcontroller, and data is displayed on the LCD. Testing of the monitoring system was carried out to ensure the accuracy of the sensor readings. Testing was carried out by comparing the voltage value on the LCD with the measurement results using a measuring instrument. The comparison value was then multiplied by 100% to obtain the error value.

Table 2. Voltage Test Data on the INA219 Sensor

Voltage Measurement with a Multimeter (V)	**LCD Display (V)**	**Difference (V)**	**Error (%)**
11.02	10.86	0.16	1.45
11.45	11.21	0.24	2.09
11.59	11.47	0.12	1.03
12.01	11.78	0.23	1.91
12.37	12.11	0.26	2.10
12.86	12.69	0.17	1.32
13.12	12.98	0.14	1.06
Average		0.18	1.56

Figure 3. Monitoring System Testing

Based on the tests conducted, it can be concluded that the average voltage error in the INA219 sensor test and compared with a multimeter measuring instrument is 1.56%, so that an accuracy level of 98.44% is obtained. This shows that the monitoring system using the INA219 sensor with the Arduino Uno microcontroller can provide fairly accurate readings in monitoring the voltage generated by the TEG. The low error value indicates that the INA219 sensor functions well in measuring voltage in real-time, and the LCD can display data accurately. Therefore, this monitoring system can be relied upon to monitor the performance of the waste-to-energy power generation system continuously.

c. Testing Photocell Sensors and Relays

This test aims to ensure that both components are functioning properly and are responsive to changes in light intensity (Zhou & Che, 2021). The first test is conducted in the morning and the final test is conducted in the evening to verify the photocell sensor's ability to detect light conditions and automatically activate the relay based on the detected light intensity.

Table 3. Photocell and Relay Sensor Test Data

Time	O'clock	Light Condition	Relay Status
Morning	06.00	ON	ON
Morning	07.00	OFF	OFF
Afternoon	18.00	OFF	OFF
Evening	19.00	ON	ON

Based on the results of photocell and relay sensor tests carried out at various times (morning, afternoon, and evening), it can be concluded that the photocell sensor functions well in detecting changes in light and controlling the relay to turn the lights on or off automatically according to the surrounding lighting conditions (Espinel, Díaz, & Vega, 2021).

e. Overall System Testing

After testing each hardware and software component, a complete system test was conducted to determine the performance of the waste-to-energy plant using a Thermoelectric Generator (TEG) by displaying sensor measurement data on the LCD and charging and distributing energy to the load. The testing process begins with the incineration of waste which produces heat (Falae, Kanungo, Chauhan, & Dash, 2019). The bottom side of the TEG is placed above the incinerator, while the cold side is cooled (water and ice) to create a large temperature difference. This temperature difference produces an

electrical voltage that is transmitted to the INA219 sensor for measurement. The data obtained from the INA219 sensor is then sent to the Arduino UNO for processing and displayed on the LCD, which is then compared with the measurement results of a digital multimeter to ensure measurement accuracy.
After that, the generated voltage is channeled to the Solar Charge Controller (SCC) to be regulated according to the battery charging capacity. Testing is carried out to ensure that the battery can be charged and store energy used to light the lights for a certain period of time (Lee et al., 2019). The photocell sensor functions to detect changes in light intensity in the surrounding environment, during the day the sensor will detect sufficient light and turn off the relay, so the lights turn off, while at night or when the light is low, the sensor will send a signal to the Arduino to turn on the relay and turn on the lights. Further testing is carried out to prove the duration of the lights on based on the capacity of the charged battery (Merlin & Chen, 2021).
Test results showed that the TEG-based waste-to-energy power generation system functioned well, generating enough electricity to automatically turn on lights and operate the lighting system according to changing lighting conditions. Thus, this test demonstrated that the system functioned according to its design and research objectives, namely utilizing renewable energy from waste for lighting.

Figure 4. Overall System Testing

CONCLUSION

Based on the results of the research and tool trials that have been carried out, the author concludes as follows:

a. The TEG-based waste-to-energy power plant successfully generates enough voltage to charge a 5Ah battery operating at 12V and power a 5W 12V DC lamp. The device uses six TEG modules connected in series, generating a voltage of 12 to 15 Volts at a temperature difference (ΔT) of 150°C to 200°C.
b. TEGs convert heat energy from waste combustion into electrical energy through the Seebeck effect. The greater the temperature difference (ΔT) between the hot and cold sides of the TEG, the greater the voltage generated. Tests show that with six TEGs, the system can generate 12 to 18 volts, enough to store energy in batteries and power lamps.

c. The monitoring system using the INA219 sensor with Arduino UNO can measure and display voltage, current, and power parameters with an accuracy level of 98.44% while the device is operating and displayed on the LCD. The information displayed on the LCD directly can facilitate monitoring the performance of the power generation system and detect damage to the device components early.

Suggestion

Based on the results of this study, here are some suggestions that can be put forward for further development:

a. The use of a water block to maintain the cool side of the TEG. The water block can help maintain a larger temperature difference between the hot and cold sides of the TEG, thereby increasing the efficiency of converting heat to electricity.
b. Integration with other renewable energy systems. This research can be expanded by integrating solar or wind power plants with waste-to-energy systems. The combination of various renewable energy sources will make the system more efficient and reliable in the long term. To improve sustainability and reduce the environmental impact of waste-to-energy systems, it is recommended to use smoke filters or exhaust gas filtration systems in the waste incineration process .

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