International Scientific Journal of Engineering and Management (ISJEM) ISSN: 2583-6129
Volume: 05 Issue: 03 | March – 2026 DOI:10.55041/ISJEM05672
An International Scholarly || Multidisciplinary || Open Access || Indexing in all major Database & Metadata

Waste to Energy: Arduino Based Thermoelectric Energy Harvesting

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ABSTRACT

There is a pressing requirement for alternative, clean, and locally available energy sources in light of the rapid rise in global energy demand and solid waste generation. Every day, heat from burning waste, hot surfaces, industrial exhaust, cooking stoves, boilers, and other thermal processes waste a significant amount of energy. It is possible to reduce reliance on conventional power sources and support sustainable waste management practices if this waste heat is able to be captured and converted into electrical energy. Utilizing thermoelectric energy harvesting, the primary objective of this project is to generate electrical power from waste heat. Based on the Seebeck effect, a thermoelectric generator (TEG) generates voltage when a temperature difference exists between its hot and cold sides.

The TEG receives heat from any hot surface or waste burning in the proposed system. In order to raise the temperature gradient and boost output voltage, a cooling fan helps keep the cold side of the device at a constant temperature. The operating temperature is tracked by a temperature sensor, and the smoke level is tracked by a smoke sensor to ensure safety when waste is burned. Temperature-based control of the fan and load is done with a W1209 thermostat module. A 162 LCD displays real-time parameters, a microcontroller (Arduino/ESP32) reads sensor values, and a relay module switches the fan or load as needed. Monitoring and safety features are provided by the system, which demonstrates a practical method for converting waste heat into electrical energy. The implementation of low-cost clean technology, pollution awareness, and energy conservation are all aided by this strategy.

KEYWORDS

Waste Heat Recovery, Thermoelectric Generator, ESP32, Energy Harvesting, Seebeck Effect, Renewable Energy

INTRODUCTION

Energy is a necessary component of modern society. The expansion of technology, population growth, and industrialization all contribute to an ever-increasing need for electricity. At the same time, the production of solid waste has grown to be a major issue for the environment. Burning or dumping a lot of waste, including plastics, paper, rubber, and biomass, can pollute the air and release harmful gases. However, significant heat is also produced by burning and hot waste sources, which typically escape to the atmosphere without producing anything useful. The process of turning waste materials into usable forms of energy like electricity, heat, or fuel is referred to as "waste-to-energy." Anaerobic digestion, gasification, pyrolysis, and steam turbine-powered incineration are all examples of conventional waste-to-energy systems. These methods work well on a large scale, but they need a complicated infrastructure and a lot of money.

Thermoelectric energy harvesting, on the other hand, provides a simpler approach to directly converting heat into electricity without the use of moving parts. A temperature difference can be converted into voltage with a thermoelectric generator. Because of this, it can be used for small-scale energy harvesting. Waste heat is captured by a thermoelectric module, monitored by sensors, and controlled by control modules like a thermostat and a relay in this project. An LCD shows real-time values so that users can see system status, smoke condition, and temperature. The goal of this project is to create a low-cost prototype that will demonstrate the idea of using waste heat to generate energy and raise awareness of alternative energy sources.

OBJECTIVES OF THE PROJECT

- Utilizing a thermoelectric generator, develop a prototype that converts waste heat into electrical energy.
- To ensure a safe operating range and monitor the heat source's temperature.
- To provide safety monitoring and smoke level detection during waste burning.
- To automatically control a cooling fan in order to maintain the thermoelectric module's temperature difference.
- To use a relay switching module to control the connected load or fan.
- To display temperature, smoke status, and output condition on a 162 LCD in real time.
- To demonstrate how the Seebeck effect and the generation of thermoelectric power work in practice.

- To spread awareness of sustainability and energy conservation at a low cost.

LITERATURE SURVEY

Literature Review Several studies have looked at how thermoelectric generators (TEGs) can turn waste heat into electrical energy. These studies emphasize the sustainable energy harvesting potential of thermoelectric technology. Yaman et al. looked into whether thermoelectric generators are effective at recovering wasted heat. (2025). Their research revealed that a thermoelectric module with 127 Bismuth Telluride elements could generate approximately 2.5 W of power with an efficiency of approximately 4.05% when the electrical load resistance and the module's internal resistance were equal. This work demonstrates the significance of optimizing operating conditions for efficient energy harvesting. In their discussion of thermoelectric energy harvesting systems (2020), Yahya et al. emphasized the capability of thermoelectric generators to directly convert wasted thermal energy into electrical energy. Additionally, their research suggested that TEG systems' performance could be enhanced and operating expenses could be reduced by incorporating control methods like maximum power point tracking (MPPT).Samantaetal. reviewed the development of thermoelectric generators for a variety of uses, including energy harvesting systems and wearable electronics. (2023).

The study pointed out that because it can generate power from low-grade heat sources like body heat, industrial heat, and environmental heat, thermoelectric technology has received a lot of attention. Thermoelectric generator systems for industrial waste heat recovery were studied by Ramirez et al. (2019) and other researchers. Depending on the temperature gradient and heat flow conditions, the thermoelectric modules they tested produced electrical power ranging from 57 W to 71 W. Recent research has also focused on combining current monitoring technologies with thermoelectric systems.

For instance, IoT-based monitoring systems that make use of microcontrollers like the ESP32 can monitor temperature gradients, measure the conditions of the environment, and improve system safety and efficiency in real time. In general, previous research demonstrates that thermoelectric generators are a dependable means of converting waste heat into electrical energy. However, there are still issues, such as a low conversion efficiency and maintaining sufficient temperature differences. This study proposes an ESP32-based thermoelectric energy harvesting system with automated control and sensor monitoring to enhance system performance and safety.

IMPLEMENTATION

The proposed waste-to-energy system uses a thermoelectric generator (TEG) to convert waste heat into electrical energy by integrating hardware components and software programming. An ESP32 microcontroller is used to control and monitor the system. Implementation of Hardware A thermoelectric generator is positioned between a cooling system and a heat source in the hardware setup. To maintain a temperature difference, the thermoelectric module's cold side is connected to a heat sink and cooling fan, while the hot side is exposed to waste material burning heat. Using the Seebeck effect, this temperature difference produces electrical voltage.

The primary processing unit that controls system operations and receives data from sensors is the ESP32 microcontroller. The heat source's temperature is measured by a DS18B20 temperature sensor, and the smoke or gas produced by waste burning is detected by an MQ-2 gas sensor. The ESP32 keeps an eye on the sensor readings all the time. The ESP32 is connected to a relay module for controlling the cooling fan. In order to help maintain the thermoelectric module's temperature difference, the microcontroller turns on the fan by activating the relay when the temperature reaches a predetermined threshold. System parameters like temperature, smoke level status, and fan operation are displayed on a 162 LCD display with an I2C interface. The thermoelectric generator's electrical energy can be measured, put to use in low-power devices, or stored in a battery for later use. Implementation of Software The Arduino IDE is used to develop the system's software, and embedded C/C++ is used to program the ESP32. The program's purpose is to carry out functions of constant control and monitoring. Reading the temperature values from the DS18B20 sensor is one of the program's primary functions. making use of the MQ-2 gas sensor to keep track of the amount of smoke. comparing the readings from the sensor to predetermined threshold values. controlling the cooling fan by activating the relay module. showing data in real time on the LCD screen. Because the system runs in a loop, the ESP32 is able to continuously monitor the conditions in the environment and adjust system behaviour in response.

EXISTING SYSTEM

The majority of current waste-to-energy systems are based on large-scale processes like gasification, biogas generation, steam turbine-based thermal conversion, and incineration plants. In most cases, these systems necessitate significant capital investment, extensive installation, regular upkeep, and skilled operators.

To prevent toxic emissions, safety and environmental control systems are also required. Waste burning is performed without energy recovery in many small setups. Simply releasing heat into the air results in a loss of energy and an increase in pollution. Additionally, there is frequently no temperature or smoke level monitoring, which can lead to unsafe conditions.

The limitations of the current system

- Conventional waste-to-energy plants need a lot of infrastructure and a lot of money.
- It is not suitable for use on a small scale due to its complicated installation and upkeep.
- In most small installations, energy recovery from waste burning is not implemented.
- Safety issues may arise if monitoring is not done in real time.
- Dangerous gases and smoke are produced when waste is burned without supervision.
- The current solutions are unsuitable for educational demonstrations because they are difficult to transport.
- There is frequently no automatic control for cooling or stabilizing the temperature.

PROPOSED SYSTEM

A prototype thermoelectric energy harvesting system based on microcontrollers that converts waste heat into usable electrical energy and displays operating parameters is proposed. A thermoelectric generator (TEG) is placed on a hot surface or in close proximity to heat from waste burning. A cooling mechanism (a fan and heat sink arrangement) supports the cold side of the thermoelectric module to maintain the module's temperature difference. The temperature of the system is measured with a temperature sensor.

To improve cooling and maintain safer operating conditions, the fan can be automatically turned on when the temperature reaches a predetermined threshold. A smoke sensor can tell you if the concentration of smoke is too high to be considered safe. These sensor values are read by the microcontroller and displayed on a 16x2 LCD screen. For reliable temperature threshold control, the W1209 thermostat module can be used in conjunction with relay switching for fan/load control.

The fan or external load is safely isolated and switched by the relay module. Energy harvesting at a low cost, safety monitoring, and real-time data display are all part of the system.

METHODOLOGY

The proposed system converts waste heat into electrical energy using a thermoelectric generator and monitors the system using an ESP32 microcontroller. To guarantee effective energy harvesting, the method includes system design, sensor integration, data monitoring, and automatic control.

System Structure

The system is designed to capture heat energy produced from waste materials and convert it into electrical energy. A thermoelectric generator (TEG) is positioned between a cooling system and a heat source. A temperature difference occurs when one side of the module is heated and the other is cooled. This temperature gradient generates electrical voltage through the Seebeck effect.The generated electrical energy can be used for low-power applications or stored in a battery for later use.

Integration of Sensors

Sensors are integrated into the system to monitor environmental conditions and ensure safe operation.Temperature Sensor DS18B20: This sensor helps determine the thermoelectric module's temperature difference by measuring the heat source's temperature. Gas Sensor MQ-2: The MQ-2 sensor detects the gases and smoke that are produced when waste is burned. It provides safety alerts when the smoke level exceeds a predetermined threshold, assisting in the monitoring of air quality. The sensor data is continuously transmitted to the ESP32 microcontroller for processing.

Control mechanism

Mechanism of Control Sensor readings are processed and system components are controlled by the ESP32 microcontroller. A relay module is connected to a cooling fan that maintains the required temperature difference across the thermoelectric module. If the temperature exceeds the predefined limit, the ESP32 activates the cooling fan. The fan is turned off if the temperature falls below the threshold. An alert message is shown on the LCD screen if the concentration of smoke is higher than the safe limit. This automatic control system improves the efficiency and safety of the waste-to-energy system.

Data Monitoring and Display

A 16×2 LCD display with I2C interface is used to show real-time system information. The display provides the following parameters:

- Temperature value
- Smoke detection status

Experimentation Methodology

The system is tested by applying heat to the thermoelectric generator while monitoring the sensor values and output voltage. The cooling fan maintains the temperature difference to improve energy generation efficiency. Included in the experimental procedure are: Applying heat to the thermoelectric module. Temperature measurement with the DS18B20 sensor. using the MQ-2 sensor to determine the amount of smoke. utilizing the relay module to manage the cooling fan. displaying the parameters of the system on the LCD screen. Observing the electrical output generated by the thermoelectric module.The thermoelectric energy harvesting system's performance is evaluated by analyzing the collected data.

CONCLUSION

To demonstrate the use of thermoelectric generation to convert waste heat into electrical energy, the project "Waste to Energy: ESP32 Based Thermoelectric Energy Harvesting System" was successfully designed and implemented. When the hot and cold sides of the thermoelectric generator (TEG) remained at different temperatures, it produced a DC output. The ESP32 microcontroller used sensors to keep an eye on the temperature and the amount of smoke, controlled the cooling fan with a relay module, and showed real-time parameters on a 162 LCD.

By cooling the TEG's cold side, the automatic fan control improved thermal stability, helped maintain a better temperature difference, and supported improved energy harvesting performance. By indicating unsafe smoke conditions, smoke monitoring added a safety feature. Overall, the prototype demonstrates that waste heat can be used to generate small amounts of energy and serves as a low-cost, efficient model for education and awareness of renewable energy.

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