

Smart Thermoelectric Energy Harvesting System with IoT Home Automation

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Abstract—This project presents a sustainable approach to converting waste heat into usable electricity using a Thermoelectric Generator (TEG) based on the Seebeck effect. To make the harvested energy viable for low-power electronics, a boost converter is implemented to step up the generated voltage. The system's output is continuously monitored via an INA219 voltage and current sensor, interfaced with an ESP8266 microcontroller, and displayed locally on an LCD. Furthermore, the system enables IoT-based load control through the SinricPro mobile application. The architecture is organized into three primary subsystems: energy generation, real-time monitoring, and remote IoT load control. By combining waste heat recovery with smart IoT technology, this project demonstrates a feasible, self-powered framework for sustainable energy management and home automation, overcoming conventional limitations associated with low conversion efficiency.

Keywords—Thermoelectric Generator (TEG), Seebeck Effect, Energy Harvesting, ESP8266, IoT, SinricPro, Boost Converter, INA219 Sensor, Sustainable Energy.

I. INTRODUCTION

At present, the demand for electrical energy is continuously increasing due to the growing use of electronic devices, automation technologies, and Internet of Things (IoT) systems. Almost every modern framework depends on a continuous and stable power supply, starting from small-scale sensors to large-scale industrial equipment. However, traditional energy resources such as fossil fuels are inherently limited in nature and significantly contribute to environmental

issues like global warming and pollution. Because of these pressing challenges, it has become imperative to explore alternative, sustainable methods of energy generation to supplement conventional grids.

One highly effective approach is energy harvesting, which involves collecting ambient energy from natural or artificial sources—such as heat, vibration,

and light—and converting them into usable electrical power. Among the different techniques available, thermoelectric energy generation is becoming increasingly popular because of its simple, solid-state operation and highly reliable performance. It directly converts heat into electricity without requiring any moving parts, rendering it exceptionally suitable for long-term, maintenance-free applications in remote or inaccessible areas. The Thermoelectric Generators (TEGs) function fundamentally according to the principle of the Seebeck Effect. Whenever there is a temperature

differential between the two sides of specialized thermoelectric materials, electrons flow from the hot side to the cold side, causing the continuous generation of voltage. By capturing waste heat from engines, industrial equipment, or household appliances, TEGs can sufficiently supply low-power devices. This project integrates TEG energy harvesting with an ESP8266-based IoT framework, allowing for continuous power monitoring and remote load control via the SinricPro cloud platform.

I. SYSTEM DESIGN AND ARCHITECTURE

The designed system effectively combines thermoelectric energy generation, precise measurement of electrical parameters, wireless communication, and remote operation through a cloud platform. The architecture supports energy collection from waste heat, continuous parameter monitoring, and remote IoT switching to ensure optimal utilization of the generated power.

The system is logically divided into three main units: the Energy Harvesting System (which converts thermal energy into electricity using a TEG and a water-cooling loop), the Energy Monitoring System (which stabilizes and boosts the

voltage, and measures output via an INA219 sensor), and the IoT-Based Load Control System (which connects to Wi-Fi to toggle relays based on user inputs). Figure 1 outlines the block diagram of this integrated approach.

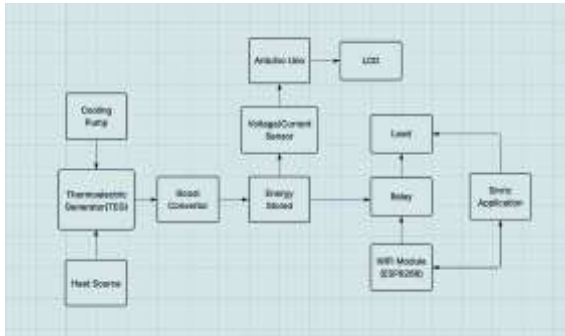


Fig. 1. Block Diagram

A. Hardware Components

The hardware is meticulously designed for efficient conversion and smart control:

- 1. Thermoelectric Generator (TEG) Module:** Converts applied heat directly into electrical direct current via the Seebeck effect.
- 2. Mini Water Pump:** Circulates coolant through a water block to continuously maintain the essential temperature gradient.
- 3. DC-DC Boost Converter (MT3608):** Amplifies the low, variable TEG voltage to a stable and usable higher level.
- 4. Voltage Regulator:** Ensures a steady power output regardless of minor input fluctuations or load changes.
- 5. Super Capacitor:** Stores the harvested energy and smoothly eliminates output voltage ripples.
- 6. ESP8266 Wi-Fi Module:** Handles core data processing, sensor communication, and secure cloud-based IoT operations.
- 7. INA219 Sensor:** A high-precision sensor deployed to accurately measure real-time voltage, current, and power.
- 8. 16×2 LCD Display:** Provides immediate, local visualization of the generated electrical parameters.
- 9. 2-Channel Relay Module:** Acts as an electromechanical switch used by the microcontroller to safely control high-power loads.
- 10. Load:** Represents the practical physical devices powered and controlled, such as LED modules or small appliances.

B. Software Tools

The software layer bridges the physical hardware components with the cloud environment. Firmware for both ESP8266 modules is written in Embedded C++ using the Arduino IDE. This custom programming facilitates seamless I2C communication with the INA219 sensor, rapid data parsing, and robust Wi-Fi networking. Furthermore, integration with the SinricPro cloud platform enables secure, API-based data exchange. This setup maps mobile application inputs to physical relay actuations with minimal latency, ensuring a highly responsive smart home

experience.

II. METHODOLOGY

The proposed TEG-Based Energy System with IoT Control follows a structured, step-by-step approach to guarantee reliable energy generation and remote load management.

System Planning

The developmental lifecycle began with a comprehensive requirement analysis, identifying the specific need for stable heat-to-electricity conversion paired with remote telemetry. Component selection prioritized ultra-low-power operation, sensor precision, and highly reliable cloud connectivity to ensure the system functions autonomously.

Functional Workflow

The integrated system seamlessly executes a continuous, seven-step operational flow:

- 1. Energy Production:** Heat is continuously applied to one side of the TEG while the opposite side is actively cooled, generating a raw electrical voltage via the Seebeck effect.
- 2. Measuring Parameters:** The INA219 sensor continuously samples the raw electrical output from the generator.
- 3. Data Processing:** The ESP8266 computes the precise voltage and current values, instantly updating the local LCD.
- 4. Voltage Boosting:** The DC-DC converter amplifies the raw, variable signal to a highly stable 5V output.
- 5. IoT Setup:** The ESP8266 establishes and maintains an active, secure link with the SinricPro cloud server.
- 6. Remote Load Control:** Authorized cloud commands from the mobile app instantly toggle the corresponding relay channels.
- 7. Energy Utilization:** The successfully actuated loads consume the harvested and safely regulated electrical energy.

TEG-Based IoT Energy System: System Flow



Fig. 2. Flow Chart

Hardware Integration and Software Development

Physical hardware nodes were meticulously assembled in a cohesive circuit to minimize internal power losses. The software was developed iteratively, focusing on non-blocking code routines to ensure that seamless, real-time monitoring functions perfectly parallel to ongoing cloud

communications.

III. TESTING AND RESULTS

Electrical Output Testing

The power output exhibited a predictable quadratic relationship with the applied temperature differential. As demonstrated in Table I, at temperature gradients of 30°C and above, the boost converter reliably maintained

a 5.0V output necessary to safely sustain the ESP8266

and associated system components. Below this critical threshold, insufficient TEG voltage caused the regulated output to drop significantly.

S.No.	Temp. Diff. (°C)	Power Output (mW)	Boosted Voltage (V)
1	10	5.4	3.2
2	20	29.4	4.5
3	30	73.8	5.0
4	40	137.8	5.0
5	50	227.5	5.0
6	60	343.2	5.0
7	70	487.6	5.0

Table 1. Power Output at Different temperature Gradients

Sensor Calibration

The readings obtained from the INA219 high-side sensor were rigorously cross-checked and verified using standard digital multimeters. As shown in Table II, the empirical data confirmed a clear linear relationship between the temperature gradient and the open-circuit

output voltage, which is characteristic of the Seebeck effect for standard TEG modules.

S.No.	Temp. Diff. (°C)	Output (V)	VoltageOutput (mA)	Current
1	10	0.12	45	
2	20	0.28	105	
3	30	0.41	180	
4	40	0.53	260	
5	50	0.65	350	
6	60	0.78	440	
7	70	0.92	530	

Table 2. Voltage VS Temperature Differential

The ESP8266 Wi-Fi module demonstrated highly stable connectivity with the SinricPro cloud server throughout the testing phase. Mobile application commands actuated the 2-channel relay module instantaneously, switching small electrical loads ON and OFF with virtually no latency. This practical validation confirmed that the prototype effectively blends sustainable energy harvesting with highly dependable smart home load control.

IV. CONCLUSION

This project successfully demonstrated a viable, self-powered prototype capable of converting waste thermal energy into stable electrical energy while simultaneously enabling IoT-based load control. By effectively utilizing a TEG module, a MT3608 boost converter, and an ESP8266 microcontroller, the system reliably generated power and continuously monitored electrical parameters via an INA219 sensor. The integration facilitated seamless remote home automation using the SinricPro mobile application. Ultimately, combining energy harvesting with smart IoT technology provides a robust, cost-effective, and environmentally friendly framework for the sustainable, maintenance-free powering of low-energy devices and distributed sensor networks.

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