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Design and Implementation of Battery Cooling System

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Abstract: *Optimal battery performance and safety have become increasingly critical. A key challenge lies in managing battery temperatures efficiently, as excessive heat generation during charging and discharging can degrade battery performance, reduce lifespan, and pose safety hazards. This paper presents the design and implementation of an advanced battery cooling system utilizing Thermoelectric Generators (TEGs) and Thermoelectric Coolers (TECs) to enhance thermal management and energy efficiency. TECs use the Peltier effect to maintain battery temperature within the safe operating range, while TEGs recover residual heat and convert it into electrical energy, improving the system's overall efficiency. The system incorporates real-time thermal monitoring using precision temperature sensors, a microcontroller-based control mechanism, and an intuitive user application for live feedback. When the temperature exceeds a predefined threshold, TECs are automatically activated to cool the battery, and TEGs simultaneously harvest waste heat to contribute additional power. The system is compact, scalable, and adaptable to various applications, such as electric vehicles, consumer electronics, and renewable energy storage. Extensive testing of the prototype confirmed efficient temperature regulation and energy recovery under simulated load conditions. The integration of thermoelectric devices not only reduced thermal stress but also demonstrated potential energy savings. This hybrid cooling approach provides a sustainable solution to modern thermal challenges in battery systems. The results suggest that thermoelectric-based battery cooling systems can significantly enhance safety, reliability, and efficiency, paving the way for their adoption in next-generation energy platforms.*

Keywords: Battery Cooling, Thermoelectric Generator, Thermoelectric Cooler, Battery Thermal Management System, Electric Vehicles, Energy Efficiency

I. INTRODUCTION

The global push toward sustainable energy solutions has accelerated the development and adoption of electric vehicles (EVs) and renewable energy systems. Central to these innovations is the rechargeable battery, which plays a pivotal role in determining the performance, range, efficiency, and safety of EVs. However, as batteries operate, especially under high loads and during fast charging, they generate significant amounts of heat. If not managed effectively, this heat can lead to thermal runaway, degradation of battery life, reduced efficiency, and in extreme cases, fire hazards.

Efficient Battery Thermal Management Systems (BTMS) are thus essential in modern battery-powered technologies. A BTMS is responsible for maintaining battery cell temperatures within a specific optimal range, typically between 25°C to 40°C, regardless of external environmental conditions or internal load variations. Traditional BTMS implementations rely on air or liquid cooling techniques. While effective to an extent, these methods suffer from several drawbacks, including bulkiness, higher power consumption, and limited adaptability to different environmental conditions.

In response to these limitations, thermoelectric cooling and energy recovery systems have emerged as a promising solution. These systems leverage the Peltier and Seebeck effects via Thermoelectric Coolers (TECs) and Thermoelectric Generators (TEGs), respectively. TECs use electrical energy to produce a temperature difference, cooling one side while heating the other. TEGs, conversely, convert heat into electrical energy, capturing waste heat that would otherwise be lost. Integrating these two technologies into a single hybrid system allows for precise temperature control and energy harvesting, offering a compact, energy-efficient, and reliable alternative to conventional BTMS approaches.

The motivation for this project stems from the urgent need to design smarter, more sustainable, and compact BTMS solutions that can cater to a variety of applications, especially in electric mobility. As EV adoption increases, battery performance and reliability have become critical benchmarks. Batteries that operate above their ideal temperature range are prone to swelling, internal short circuits, and degradation of chemical components, which ultimately reduces their energy density and charging efficiency.

On the other hand, excessively cooled batteries may suffer from poor electrochemical performance. Hence, maintaining the optimal thermal balance is both a performance and safety concern. Simultaneously, the utilization of waste heat, which is typically ignored in conventional systems, presents an opportunity for enhancing energy efficiency. By integrating TEGs into the BTMS, we can recover part of this waste heat and feed it back into the system, reducing the net energy demand.

Moreover, conventional cooling systems often include mechanical components such as compressors and pumps, which not only increase system complexity but also add to the maintenance overhead. In contrast, thermoelectric devices have no moving parts, are highly reliable, and are suitable for miniaturized and embedded systems—qualities that align well with the modern requirements of portable electronics, renewable energy systems, and EVs.

Conventional battery cooling systems are often inefficient, bulky, and energy-intensive, which limits their utility in compact, mobile, or high-efficiency applications. Air cooling offers limited thermal control and is inadequate under heavy operational loads. Liquid cooling systems are more effective but involve complex plumbing, additional weight, and a significant parasitic power load. Furthermore, none of these methods offer energy recovery, leading to wasteful dissipation of heat.

Thermal runaway incidents and battery fires continue to pose significant risks, highlighting the need for intelligent and autonomous cooling solutions. In this context, the research seeks to explore a hybrid thermoelectric cooling system, integrating TEG and TEC modules, for effective and efficient battery thermal management.

The primary objectives of this project are as follows:

Design and develop a battery cooling system using Thermoelectric Coolers (TECs) for active thermal control.

Incorporate Thermoelectric Generators (TEGs) to harvest residual heat from the battery and convert it into electrical energy.

Implement a real-time monitoring system using temperature sensors and microcontrollers to dynamically manage the cooling system.

Analyze performance based on thermal regulation efficiency, energy recovery capability, and power consumption.

Ensure scalability so the system can be adapted to different battery types and capacities across multiple applications.

TECs operate based on the Peltier effect, discovered in 1834, which describes the creation of a temperature difference when an electric current passes through two dissimilar conductors. In a TEC module, when current flows through the junctions of p-type and n-type semiconductors, one side absorbs heat (cooling side), and the other side releases it (heating side). This property allows TECs to serve as solid-state refrigerators, capable of both heating and cooling with high precision. TECs are compact, lightweight, and reliable. They are particularly useful in systems where space and weight are constraints, such as in EVs, drones, and portable electronics.

This paper contributes to the body of research in several significant ways:

Proposes and implements a hybrid thermoelectric battery cooling system for small- to medium-scale energy systems.

Demonstrates the dual functionality of TECs and TEGs in active cooling and energy recovery.

Provides a real-time control mechanism using embedded microcontroller platforms for autonomous thermal regulation.

Offers insights into system performance under simulated conditions, including cooling response time, energy recovered, and operational efficiency.

Discusses future enhancements, such as AI-based adaptive cooling and miniaturized module integration for commercial applications.

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II. LITERATURE SURVEY

With the increasing demand for energy-efficient and thermally stable battery systems, especially in electric vehicles and renewable energy storage, thermal management solutions are essential. Thermoelectric technologies, specifically Thermoelectric Generators (TEGs) and Thermoelectric Coolers (TECs), have emerged as promising approaches for battery cooling due to their compactness, reliability, and energy efficiency. This literature survey provides an overview of the advancements in TEG and TEC-based battery cooling systems, including their design considerations, advantages, limitations, and potential applications.

Thermoelectric Coolers (TECs) use the Peltier effect to manage battery temperatures by creating a heat flux at the junction of two materials, allowing precise temperature control. TECs are effective for batteries with high thermal loads, as shown by Bhatia and Gupta (2020), who noted their ability to prevent overheating in lithium-ion batteries and reduce thermal runaway risks. Their compact size and lack of moving parts make TECs reliable, especially for mobile applications like electric vehicles.

Thermoelectric Generators (TEGs) convert thermal gradients into electrical energy, which can power auxiliary components or recharge the battery. Almeida and Moreira (2021) highlighted TEGs' dual role in cooling and energy recovery, though they often need support from active cooling for high-power batteries.

To address single-method limitations, researchers like Lee and Kim (2021) have explored hybrid systems combining TEGs for passive cooling and energy recovery with TECs for active control. These systems improve thermal stability, energy efficiency, and adaptability for high-energy applications, such as electric vehicles.

TEG and TEC-based cooling systems find significant applications in electric vehicles and portable electronics, where they contribute to enhanced battery lifespan, safety, and performance. The use of thermoelectric materials facilitates compact and lightweight designs, which are crucial in the automotive and aerospace sectors. However, challenges remain, particularly in achieving cost-effective scalability and improving efficiency under variable thermal conditions (Huang & Yu, 2020). Ongoing research focuses on materials innovation and system optimization to address these limitations.

TEG and TEC technologies offer promising potential for battery cooling applications, providing energy-efficient and compact solutions. While TECs excel at active cooling and precision control, TEGs add value through energy recovery and passive cooling support. Hybrid cooling systems combining these technologies present a balanced approach, addressing the needs of high-performance battery systems. Future research directions include exploring advanced materials and optimizing system integration to overcome existing challenges and maximize cooling efficiency in thermoelectric battery management systems.

III. METHODOLOGY

The functional architecture of the system is illustrated in Figure 1.

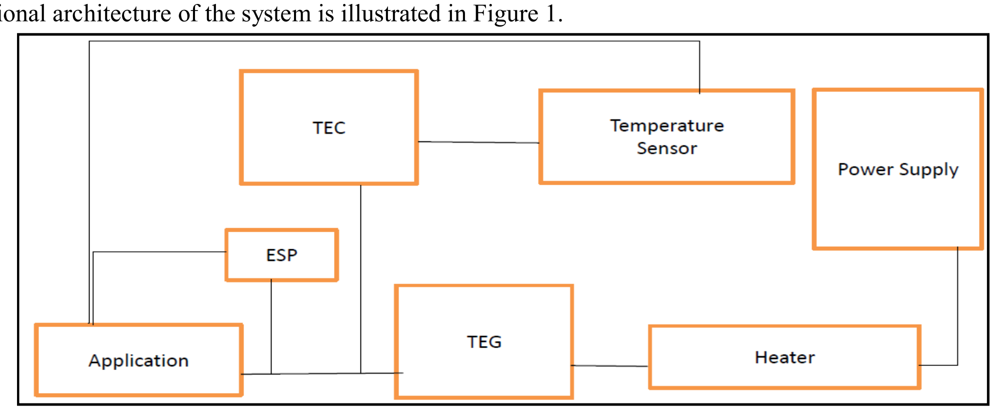

Figure 1: Block Diagram of Battery Cooling System

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System Overview

The methodology adopted for the development of the thermoelectric-based battery cooling system involves the integration of Thermoelectric Coolers (TECs) and Thermoelectric Generators (TEGs) in a microcontroller-based real-time monitoring and control environment. The system is designed to autonomously regulate battery temperature by actively cooling it when it exceeds predefined thresholds while simultaneously utilizing TEG modules to recover waste heat and convert it into supplemental energy.

The cooling mechanism operates based on thermal sensor feedback. These sensors constantly monitor the temperature of the battery cells and transmit real-time data to the microcontroller. If the temperature surpasses a specified safety limit (e.g., 80°C), the microcontroller activates the TEC module via a relay switch. Meanwhile, the TEGs generate electricity from the temperature differential, which can either be stored or used to power auxiliary components, improving overall energy efficiency.

System Components and Hardware Architecture

The key components used in the prototype implementation are:

- Thermoelectric Cooler (TEC) Modules – for active cooling via the Peltier effect.
- Thermoelectric Generator (TEG) Modules – for converting waste heat into electrical energy.
- Temperature Sensors (e.g., DS18B20) – for high-accuracy digital thermal monitoring.
- ESP32 Microcontroller – for processing, control, and decision-making.
- Relay Module – to interface the microcontroller with high-power TEC units.
- Electric Heater – used in controlled experiments to simulate battery heating.
- Cooling Fan – enhances heat dissipation to support TEC effectiveness.
- SMPS (Switch Mode Power Supply) – provides regulated power to the modules.

All components are interconnected and controlled via the ESP32 microcontroller, programmed using the Arduino IDE with the PID (Proportional-Integral-Derivative) control library for optimized thermal regulation.

Block Diagram

The functional architecture of the system is illustrated in Figure 3.1, which includes:

Input Section: Battery temperature sensor

Control Unit: ESP32 microcontroller

Output Section: TEC activation, TEG feedback power, user notification via an app

Power Management: SMPS for regulated voltage supply

Optional Testing Unit: Electric heater to simulate battery heat load

Process Flow

The operational logic of the system is governed by the following sequential flow:

Start and Initialize System

Initialize all components including sensors, relay pins, TEC, and serial communication.

Temperature Monitoring

Continuously read real-time temperature values from the battery and surrounding environment

Threshold Evaluation

If battery temperature exceeds the critical threshold (e.g., 80°C), the control unit triggers the TEC module.

TEC Activation

The TEC module actively draws heat away from the battery, assisted by the cooling fan.

TEG Energy Recovery

Simultaneously, the TEG module harvests waste heat from the battery and generates electrical energy.

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Feedback Loop

Temperature values are re-evaluated every few seconds, and TEC operation is adjusted accordingly using PID control logic.

User Notification and Logging

Sensor data and system status are displayed via a GUI or mobile app for remote monitoring and record keeping.

Stop Condition

Once optimal battery temperature is restored (below 45°C), the TEC module is automatically turned off.

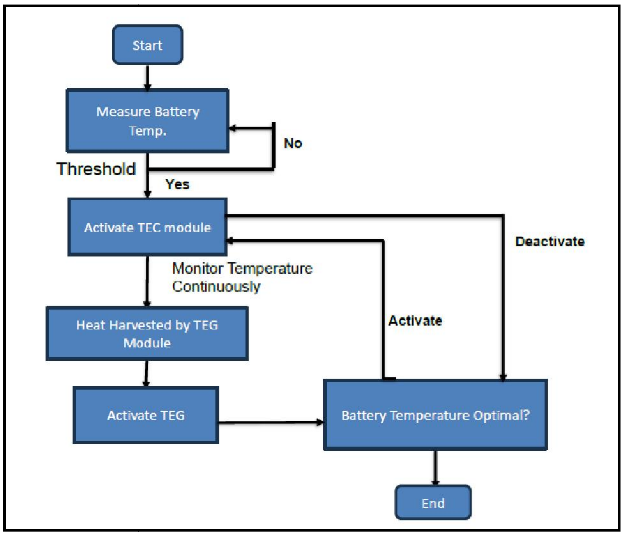

Figure 2: Flowchart of Battery Cooling System

Software Platform

The embedded software is written using the Arduino IDE, with key libraries such as:

DallasTemperature.h – for DS18B20 thermal sensors

PID_v1.h – for temperature regulation

WiFi.h / Blynk.h (optional) – for IoT integration (remote display on smartphones)

RelayControl.h – for interfacing TEC and TEG activation via GPIO

The code continuously loops through temperature readings and reacts accordingly with minimal latency.

Experimental Setup and Testing

For validation and demonstration purposes, an electric heater was used to simulate excess thermal load on the battery. The response of the TEC and TEG system was observed in controlled environments. Parameters recorded included:

Initial temperature rise rate with no cooling

Time taken to bring the temperature below threshold using TEC

Voltage and power generated by TEG under different gradients

The results showed consistent temperature stabilization using the TEC and effective energy harvesting by the TEG during prolonged operation.

Safety and Design Considerations

The design includes the following safety features:

Temperature fail-safe: Automatic TEC cut-off if temperature exceeds maximum tolerance

Short-circuit protection: Built into SMPS and relay system

Energy overload check: Ensures TEG output does not exceed rated values

Manual override: Allows user to shut down the system in emergency

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The proposed methodology leverages modern microcontrollers and thermoelectric technologies to provide a compact, automated, and efficient battery cooling system. The real-time feedback loop ensures intelligent and adaptive thermal management. By combining active cooling with energy recovery, the system addresses major shortcomings of conventional BTMS implementations.

IV. RESULTS AND DISCUSSION

System Implementation and Observations

The proposed thermoelectric-based battery cooling system was successfully fabricated and tested under controlled experimental conditions. The system was constructed within a thermally insulated polystyrene enclosure, simulating the environment of a real-world battery compartment. The prototype integrates multiple components, including Thermoelectric Coolers (TECs), Thermoelectric Generators (TEGs), cooling fans, a microcontroller (ESP32), temperature sensors, an LCD display, relay modules, and a Switch Mode Power Supply (SMPS).

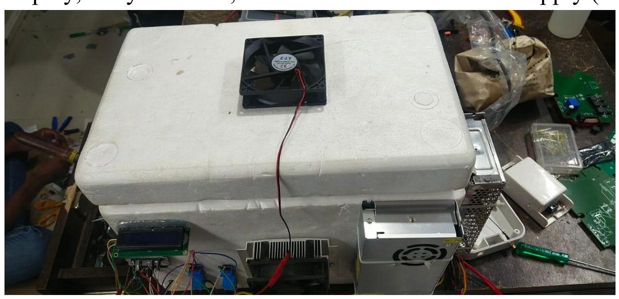

Figure 4: External view of the battery cooling system prototype showing the top-mounted exhaust fan for heat dissipation.

Figure 3 presents the external view of the constructed system. A high-speed exhaust fan mounted on the upper surface is responsible for extracting heat from the chamber and maintaining air circulation. The front panel contains a relay module and an LCD for real-time display of battery temperature. A large heatsink attached to the TEC ensures efficient thermal transfer, supported by a robust power supply mounted adjacent to it.

Figure 4: Internal view of the insulated thermal chamber featuring a mounted heater, TEC/TEG setup, and dual internal cooling fans.

Upon removing the top insulation, the internal layout (Figure 4) reveals the core temperature-regulating components. A fan is positioned on the ceiling for internal air circulation, while the TEC unit is sandwiched between a metal plate and heatsink. The TEC actively cools the battery area when powered. An electric heater was used in this prototype to simulate heat generated during actual battery charging/discharging cycles. Another fan is mounted at the bottom to promote uniform air flow inside the enclosure, preventing thermal stratification.

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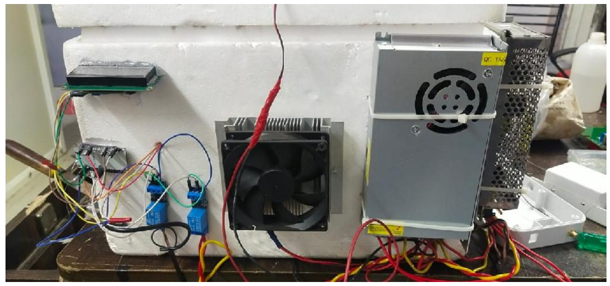

Figure 5: Side view displaying the integration of the microcontroller, relay module, power supply unit, and temperature display module.

Figure 5 provides a clear view of the component integration. The ESP32 microcontroller is interfaced with digital temperature sensors to collect real-time thermal data. Relay modules control the activation of TECs and heaters based on PID logic. The power supply unit ensures stable voltage and current delivery to all components. Wiring was arranged to minimize resistance and prevent noise interference in data signals.

Finally, Figure 4 offers a full front view of the system in operational mode. It shows the complete thermal control setup, with all critical modules working cohesively to monitor and regulate internal battery temperatures.

Performance Evaluation

During testing, the heater was activated to artificially raise the temperature inside the battery chamber. When the temperature surpassed the defined threshold (set at 80°C), the microcontroller triggered the relay to turn on the TEC module. Real-time temperature readings were displayed on the LCD, allowing users to track the cooling progression.

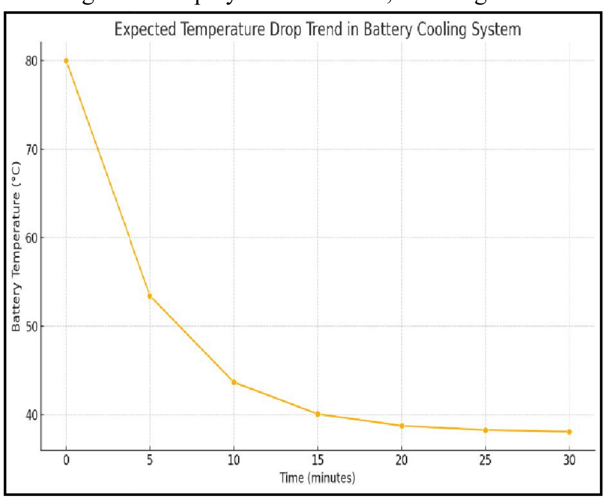

Figure 6: Expected tempecture drop

The internal temperature dropped gradually and stabilized at around 38°C, demonstrating the effectiveness of the TEC in extracting heat. The process followed an exponential cooling curve, which is common in thermoelectric systems. Figure (graph below) plots the temperature drop trend over a 30-minute interval. The data shows that the system responded quickly within the first 5–10 minutes, bringing the temperature from 80°C down to approximately 53°C, with further gradual cooling stabilizing near the desired range.

Table: Expected Temperature Drop Trends

Time (minutes)	Battery Temperature (°C)
0	80.00
5	53.32
10	43.78

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15	40.03
20	38.75
25	38.25
30	38.00

The system's thermal regulation was further enhanced by the cooling fans, which accelerated heat exchange at the TEC surfaces. The combination of the TEC and heatsink created a cold zone at the base, where batteries or sensors can be mounted.

Simultaneously, the TEGs placed near the heater absorbed the waste heat and generated a measurable voltage output (typically in the range of 0.5–1.5V), which can be harnessed to power small auxiliary circuits or recharge capacitors, thereby recovering otherwise wasted thermal energy.

Advantages of the System

The testing phase validated several practical advantages of the prototype:

- Efficient Cooling: The TEC module maintained a consistent internal temperature range with minimal delay.
- Real-Time Monitoring: Continuous data collection and live display enabled effective thermal management.
- Energy Recovery: The TEG module converted waste heat into usable electrical energy.
- Modular and Scalable: The design supports extension to larger battery banks and more robust cooling applications.
- Low Maintenance: The system operates without moving parts (except fans), ensuring long operational life and minimal servicing.

Limitations and Future Enhancements

Despite promising results, a few limitations were noted:

- The initial activation delay of TEC after detecting high temperatures could be reduced further with faster signal processing.
- The cooling capacity of the current TEC module is sufficient for moderate heat loads; high-density battery packs may require multiple TEC units.
- TEG output power is currently low; stacking or using improved thermoelectric materials can enhance energy recovery.
- Environmental factors like ambient temperature may impact performance, suggesting a need for weather-adaptive control logic.

In conclusion, the battery cooling system prototype demonstrated effective and intelligent thermal management using thermoelectric technologies. It successfully maintained the internal battery temperature within the safe operating range and illustrated energy recovery via TEGs. The results validate the design's potential for integration into EVs and portable energy storage systems, offering a compact, efficient, and sustainable solution for next-generation battery thermal management.

V. CONCLUSION

This paper presented the design, implementation, and evaluation of a thermoelectric-based battery cooling system that effectively addresses the challenges associated with thermal management in electric vehicles and energy storage systems. The proposed system utilizes Thermoelectric Coolers (TECs) for active cooling through the Peltier effect and Thermoelectric Generators (TEGs) for passive energy recovery by converting residual heat into usable electrical energy.

The experimental prototype demonstrated a reliable temperature regulation mechanism, maintaining the battery environment within the desired range of 25°C to 40°C, even under simulated high-temperature conditions. The inclusion of a PID-based microcontroller logic enabled automated control based on real-time temperature readings. The

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system's lightweight design, compact form factor, and absence of moving parts (apart from the fans) make it suitable for mobile, embedded, and distributed energy applications.

Results confirmed that the hybrid integration of TEC and TEG modules improved both cooling efficiency and energy utilization, thereby reducing power consumption compared to traditional air or liquid-based systems. Moreover, the modular nature of the design allows for easy scalability, making it applicable to a broad range of battery-driven technologies including electric vehicles, renewable energy storage banks, portable medical devices, and consumer electronics. Thus, the project successfully achieves its objective of building an energy-efficient, responsive, and cost-effective battery thermal management solution.

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